An examination of binocular reading fixations based on sentence corpus data

An examination of binocular reading fixations based on sentence corpus data

Antje Nuthmann

Department of Psychology, University of Edinburgh, Edinburgh, UK

Reinhold Kliegl

Department of Psychology, University of Potsdam, Potsdam, Germany

Binocular eye movements of normal adult readers were examined as they read single sentences. Analyses of horizontal and vertical fixation disparities indicated that the most prevalent type of disparate fixation is crossed (i.e., the left eye is located further to the right than the right eye) while the left eye frequently fixates somewhat above the right eye. The Gaussian distribution of the binocular fixation point peaked 2.6 cm in front of the plane of text, reflecting the prevalence of horizontally crossed fixations. Fixation disparity accumulates during the course of successive saccades and fixations within a line of text, but only to an extent that does not compromise single binocular vision. In reading, the version and vergence system interact in a way that is qualitatively similar to what has been observed in simple nonreading tasks. Finally, results presented here render it unlikely that vergence movements in reading aim at realigning the eyes at a given saccade target word.

Keywords: reading, eye movements, binocularity, fixation disparity, vergence

Citation: Nuthmann, A., & Kliegl, R. (2009). An examination of binocular reading fixations based on sentence corpus data. *Journal of Vision, 9*(5):31, 1–28, http://journalofvision.org/9/5/31/, doi:10.1167/9.5.31.

Introduction

When reading, we move our eyes across the page because of visual acuity limitations. Fine visual discriminations can only be made within the fovea, i.e., the central 2° of vision. Thus, visual acuity is best in the fovea, and it rapidly decreases toward the parafovea and periphery. When reading our eyes make quick ballistic movements, that is, saccades (see Figure 1), to bring a new region of text into foveal vision. During fixations, the periods between saccades, the eyes remain relatively still for about 250 ms, and visual processing can take place. At one level, reading requires the oculomotor and perceptual coordination of the two eyes. Here, we examine various aspects of binocular coordination in reading. The aim of the present work is twofold. First, we investigate whether central findings on binocular coordination obtained with simple scanning paradigms generalize to reading, i.e., a real-world visual-cognitive task involving sequences of saccades. Second, we seek to extend the existing literature on binocular coordination in reading. In the following, basic concepts of human vision that are relevant for the present work are defined. We will then summarize key findings from (1) basic oculomotor research, and (2) research on binocular coordination in normal continuous reading. Finally, we will convey how the present work extends this literature.

In human vision, gaze direction for each eye is defined by the orientation of the *line of sight,* i.e., the line extending from the center of the fovea through the nodal points of the eye into visual space (cf., Collewijn, Erkelens, & Steinman, 1997). The two lines of sight intersect at the *binocular fixation point,* forming the *vergence angle* γ (Figure 2). When a perceiver looks at some part of a text (or more generally put an object), the stimulus patterns on the retinas of the two eyes differ because the eyes are located in different positions in space. We can relate points in space to their retinal representations and to the perceptions they produce by utilizing the concept of the *horopter*. The longitudinal horopter is the surface in space containing all points that, for a given binocular fixation point, stimulate corresponding retinal points in the two eyes (Hershenson, 1999). All points not on this surface stimulate noncorresponding retinal points, resulting in disparity between the two retinal images (i.e., *retinal disparity*). Horizontal retinal disparity is necessary for experiencing difference in depth. Moderate disparity does not compromise single binocular vision. When the noncorresponding retinal points in the two eyes fall within *Panum's area,* the perceptual image is fused. Studies on Panum's fusional area typically use nonlinguistic simple stimuli like lines or gratings. Stimuli are presented dichoptically, i.e., one to each eye of the participants. Fusing limits are determined with methods ranging from verbal report and adjustment methods to criterion-free methods (see Heckmann & Schor, 1989, for discussion). For example, a recent study reported an upper disparity limit of about 32–40 min of arc for the horizontal meridian, which is larger

doi: 10.1167/9.5.31 Received August 3, 2008; published May 29, 2009 ISSN 1534-7362

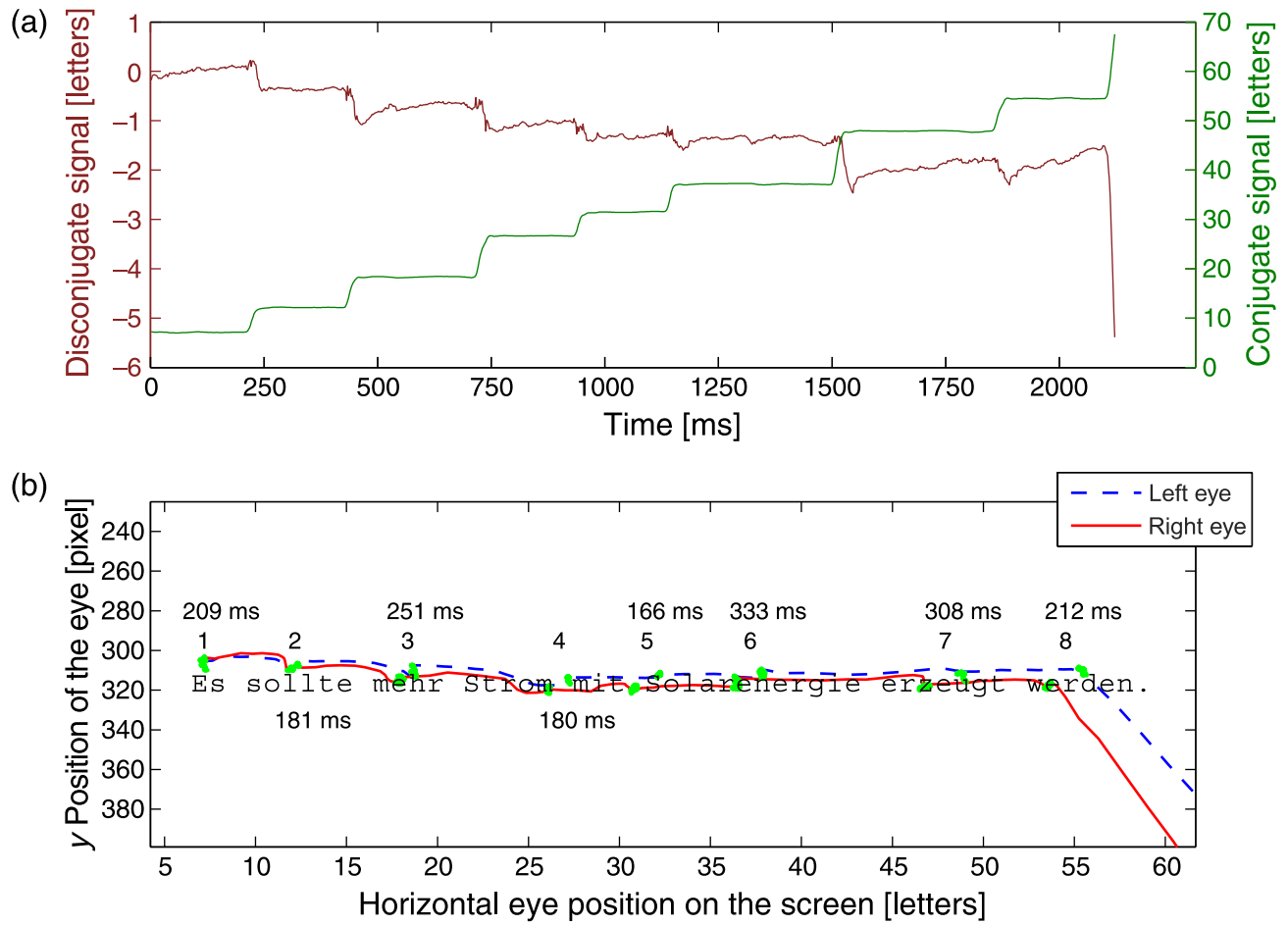

Figure 1. Space–time diagram of changes in horizontal eye positions while reading a sentence from the Potsdam Sentence Corpus. (a) The conjugate signal [(*L* + *R*)/2] and disconjugate signal (*R* − *L*) are plotted at different scales. (b) Example sentence with traces for right eye (straight, red) and left eye (dashed, blue) superimposed; fixations in green. The down-and-right movement signaled the end of reading; numbering indicates fixation sequence; fixation durations are listed on top or below the sentence.

than the limit in the vertical meridian, about 19.2–25.6 arc min (Qin, Takamatsu, & Nakashima, 2006). The size and shape of Panum's fusional area depends on the spatial and temporal characteristics of the stimulus; e.g., larger objects remain fused over a greater range of disparities than smaller objects (Schor, Wood, & Ogawa, 1984). More disparate images rival each other and one is suppressed. Large disparities will result in the perception of double images.

Binocular gaze shifts in space are achieved by simultaneous operation of two classes of eye movement subsystems: *conjugate* and *disconjugate*. Conjugate (or version) movements, predominantly saccades, denote parallel movements of the eyes in the same direction (Figure 1a provides an exemplary conjugate signal observed in reading). In contrast, disconjugate (or vergence) movements denote movements of the eyes in opposite directions (Cassin & Rubin, 2006). In case of convergence, the eyes move inward, i.e., toward each other. In case of divergence, the eyes move outward, i.e., away from each other. As an example, Figure 1a shows the disconjugate signal retrieved from the space–time diagram of changes in horizontal eye positions while reading a sentence. When viewing a target at an approximately flat surface, disconjugate eye movements might aim at aligning the two eyes at the target position. For a gaze shift between targets at different depths, the vergence system responds in a manner that reduces the resulting retinal disparity, thus maintaining single vision. The distinction between conjugate and disconjugate signals was first formalized by Hering (1868) in his "law of equal innervation" presuming complete independence of the conjugate and disconjugate systems.

Binocular coordination of saccades in nonreading tasks

Following this assumption, many experimental studies of changes in fixation have used targets intended to produce either conjugate saccades or pure vergence movements. For example, to investigate conjugate saccades,

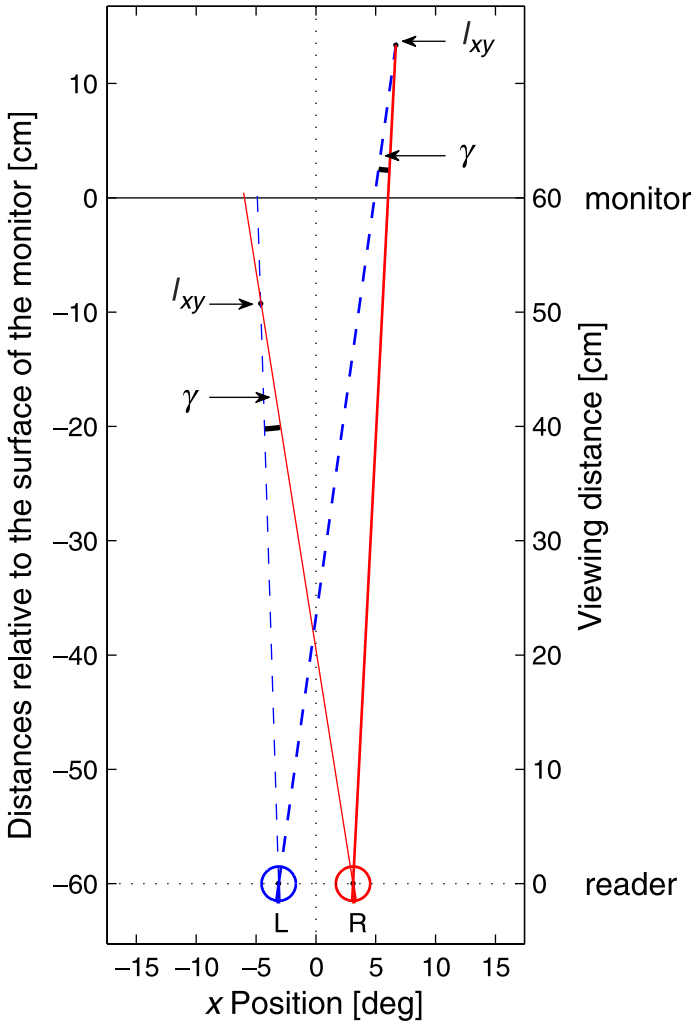

Figure 2. Schematic visualization of two disparate eye fixations. Top view of the horizontal plane. The figure reflects the ratio of distances in the experiment. Distances are given in Cartesian coordinates with the origin in the midpoint between the centers of the eyes. The distance between reader and monitor (i.e., the viewing distance) is expressed in centimeters while horizontal distances are expressed in degrees, relative to the midpoint between the centers of the eyes [0°]. Angles and distances are exact for an inter-ocular distance of 6.5 cm. Fixations were measured on the surface of the monitor. Lines of sight for the left eye (L) are represented by broken lines, lines of sight for the right eye (R) are represented by solid lines. The fixation on the left half of the monitor shows crossed disparity: The left eye fixates to the right of the right eye. In this case, the lines of sight intersect at a point l_{xyz} in front of the monitor. The fixation on the right half of the monitor shows uncrossed disparity; the binocular fixation point l_{xyz} is located beyond the monitor. The intersection of the lines of sight forms the vergence angle γ.

Collewijn and colleagues developed a paradigm where participants were asked to look back and forth between light emitting diodes (LEDs) at the pace of a metronome (e.g., Collewijn, Erkelens, & Steinman, 1988a, 1995; Collewijn et al., 1997). To avoid any stimulation of vergence, in some of their experiments stimuli were presented on iso-vergence circles (i.e., circles passing through the rotational centers of the two eyes and through the targets). In contrast, studies investigating pure vergence movements would present targets in the mid-sagittal plane at varying viewing distances (e.g., Rashbass & Westheimer, 1961). The amplitude of the vergence movement tends to be dysmetric, i.e., moving gaze from a near to a far target leads to excessive convergence (over-convergence), and moving gaze from a far to a near target to insufficient convergence (under-convergence; Cornell, MacDougall, Predebon, & Curthoys, 2003). Convergence is usually faster than divergence (Hung, Zhu, & Ciuffreda, 1997; see Straumann, 2007, for a recent review on disconjugate eye movements). If version and vergence movements were completely independent, saccades would be superimposed upon a slower ongoing vergence movement (see Figure 6 in Yarbus, 1957, for illustration). Research employing simple scanning tasks has shown, however, that normal human eye movements often violate Hering's Law (e.g., Collewijn et al., 1995, 1997; Zee, Fitzgibbon, & Optican, 1992). Much of the total vergence change takes place during the saccade. During a saccade, the eyes initially diverge, but convergence occurs in the latter part of the saccade, continuing into the fixation period following the saccade (e.g., Collewijn et al., 1988a, 1997). This pattern originates from an asymmetry between saccades made by the abducting (temporally moving) and adducting (nasally moving) eye. In a typical horizontal saccade, the abducting eye has a larger amplitude, a higher peak velocity, and a shorter duration (Collewijn et al., 1988a). The transient divergence during saccades was confirmed by an investigation of the binocular fixation point, which showed an outward-looping, curved trajectory (Collewijn et al., 1997). The loops were disproportionately larger for far than for near targets, due to the nonlinear relation between vergence and viewing distance (but see Yang & Kapoula, 2003, suggesting that effects of target distance cannot be due to geometry alone). Furthermore, the relative contributions of the two eyes to post-saccadic (or intra-fixational) vergence appear to be asymmetric (Collewijn et al., 1988a; Enright, 1998; but see Collewijn et al., 1997, reporting symmetry). Gaze shifts in a natural setting typically require composite eye movements, i.e., movements between targets that differ simultaneously in both direction and distance from the observer. A number of studies investigated combined version and vergence; a key finding is that version accelerates vergence while vergence slows down version (Collewijn et al., 1995). Finally, little is known about vertical fixation disparities. Collewijn et al. (1997) note that their recordings of the vertical components of horizontal binocular eye movements indicated only small vertical disparity. In addition, vertical conjugacy for vertical saccades is good though not perfect (Collewijn, Erkelens, & Steinman, 1988b).

Binocular coordination of saccades in reading

Typically, basic studies on binocular coordination ask participants to make a saccade to a well-defined target in space. Consequently, these investigations mostly focus on saccades (gaze shifts) rather than fixations (inter-saccadic intervals). However, many real-world visual-cognitive tasks, like reading, require us to program sequences of saccades. Reading creates a visually well-structured environment, requiring mostly horizontal saccades in the direction of print. Visual processing of the text is achieved during fixations. Therefore, the natural interest of reading research is primarily directed to binocular coordination during fixations (rather than saccades). Further, results are typically reported in character spaces rather than degrees of visual angle. It appears that reading saccades are executed to traverse a certain number of characters rather than a certain amount of visual angle (Morrison & Rayner, 1981). Reading predominantly requires version movements, but vergence movements also occur (Hendriks, 1996). In the present study, readers were presented with single sentences on a CRT monitor. Binocular eye movements were recorded to measure the *fixation disparity,* that is, the distance between the two fixation points on the plane of fixation. Basically, the recorded binocular fixation positions reflect the intersection of the two hypothetical lines of sight with the surface of the monitor the text is presented on. If the binocular fixation point (i.e., the point of intersection) is precisely on that surface, we will observe perfect alignment of the eyes (see data points at the origin of the coordinate system of disparities in Figure 3a). If the binocular fixation point is not precisely on the surface of the monitor, we will observe fixation disparity. According to the direction of the fixation disparity, we distinguish positive and negative disparities. Fixation disparity is positive (or uncrossed) if the right eye fixates to the right of the left eye. Importantly, positive fixation disparities occur when the binocular fixation point is located beyond the surface of the monitor (Figure 2). Fixation disparity is negative (crossed), if the left eye's fixation on the text precedes that of the right eye. In that case, the lines of sight will intersect in front of the monitor. Recently, a nomenclature of three alignment conditions for fixation disparities in reading has been proposed, taking both the direction and magnitude of disparity into account (see below, Liversedge, White, Findlay, & Rayner, 2006). Fixational disparity is accompanied by retinal disparity.

Binocular coordination of saccades and vergence control have become a central topic in eye movement research on dyslexia (see Kirkby, Webster, Blythe, & Liversedge, 2008, for a review). Literature on binocular coordination in normal continuous reading, however, is rather sparse. Almost all empirical research on eye-movement control in reading has been based on recordings of the movements of just one of the two eyes, typically the right eye. Research by Heller and Radach (1999) established that horizontal fixation disparity does exist in reading, i.e., the eyes do not necessarily fixate the same point within a word. Recently, Liversedge and colleagues systematically investigated the direction and magnitude of fixation disparities in reading, proposing the following classification: Fixations are categorized as aligned (where both eyes were within one character of each other) and nonaligned (where both eyes were more than one character apart; Liversedge, White et al., 2006). Nonaligned fixations are further classified as uncrossed vs. crossed. A fixation disparity is crossed if the left-eye point of fixation is more than one character to the right of the right-eye point of fixation. Using this classification, recent reports of aligned fixations ranged from 48% (Blythe et al., 2006) to 55% (Juhasz, Liversedge, White, & Rayner, 2006). Estimates of crossed fixation disparities ranged between 8% (Liversedge, White et al., 2006) and 18% (Juhasz et al., 2006) of all considered reading fixations. Despite the numerical differences, this research suggests that crossed fixations are clearly outnumbered by uncrossed fixations (27–39%). However, there is inter-reader variability in the frequency of crossed and uncrossed fixations in that some readers make more crossed than uncrossed fixations (Juhasz et al., 2006). Furthermore, children show a higher proportion of crossed fixations than adults (Blythe et al., 2006). During the time course of fixation, fixation disparity is reduced by vergence movements (Hendriks, 1996). The author compared vergence velocities for the initial 80 ms with velocities for the entire fixation period, showing that vergence velocity decreases over time (see also Collewijn et al., 1988a). The magnitude of fixational vergence movements is positively correlated with incoming saccade length (Heller & Radach, 1999) and fixation duration (Liversedge, White et al., 2006). There is conflicting evidence on how the magnitude of fixation disparity changes across the line of text. When reading the first line of multi-line text, fixation disparity (as measured 150 ms after fixation onset) increased during the course of successive fixations within a line (Heller & Radach, 1999). In contrast, in a study by Liversedge, White et al. (2006) the magnitude of end-of-fixation disparity seemed to be quite stable across the sentence and/or screen. Furthermore, recent results indicate that fixation disparity is independent of cognitive load imposed by the reading material (Juhasz et al., 2006; but see Heller & Radach, 1999). So far, research has ignored vertical disparities. Exploratory analyses in the present paper begin to fill this gap.

With the present work we seek to extend the literature on binocular coordination in reading while drawing inspiration from basic oculomotor research on binocular coordination. The work derives from an analysis of sentence reading corpus data comprising eye-movement data from more than 200 readers having read more than 100 sentences each. The data were collected over several

years to provide an empirical database for a computational model of eye-movement control in reading (Engbert, Nuthmann, Richter, & Kliegl, 2005).[1] Here, we report binocular aspects of this comprehensive data set, adding to our current knowledge about binocular coordination in reading in a number of ways. We report that in our corpus of binocular fixations in reading, fixation disparities are predominantly crossed (rather than uncrossed as suggested by previous research). Novel analyses of the binocular fixation point in reading elaborate on the implications of crossed and uncrossed fixation disparities for vergence control. We also investigate the time course of saccade–vergence interactions in reading and consider the independent contributions of the two eyes to intra-fixational vergence. Furthermore, we explore how the magnitude and direction of fixation disparity change as the eyes move from left to right through the sentence. Bridging the gap to more conventional research on eye-movement control in reading, we investigate the effect of horizontal eye disparity on spatial measures of eye-movement control in reading, notably on the well-established horizontal preferred viewing location. Finally, we go beyond previous research in that a subset of analyses describes binocular fixations with two-dimensional disparities, thus taking not only horizontal but also vertical eye disparities into account.

Methods

Participants

Altogether 245 participants contributed to the reading experiment. The database consists of four sub-samples: 110 university students (M = 22.22, SD = 3.53, range 18 to 38 years), 70 older adults (M = 69.61, SD = 4.73, range 60 to 84 years), 41 high school students (M = 17.80, SD = 0.93, range 16 to 20 years), and 24 subjects of middle age (M = 43.70, SD = 8.29, range 21 to 57 years). They were all native speakers of German. All participants had normal or corrected-to-normal vision. Participants were tested with a multiple-choice measure of vocabulary (Lehrl, 1977) and the digit symbol substitution test from the HAWIE intelligence test for adults (Wechsler, 1964). Young and older adults showed the typical pattern of equivalence in the vocabulary measure and significant differences in digit symbol substitution (see Kliegl, Grabner, Rolfs, & Engbert, 2004). Detailed information on the age, sex, and eye dominance of participants as well as their performance in the measure of vocabulary and the digit symbol substitution test can be found in Nuthmann (2006). Sessions lasted about one hour. Participants were paid an equivalent of €5 per hour or received credit in partial fulfillment of study requirements.

Apparatus

Sentences were presented in black on a white background on the centerline of a 21-inch EYE-Q 650 Monitor (832 × 624 resolution; frame rate 75 Hz; font: regular New Courier 12) controlled by an Apple Power Macintosh G3 computer. Data were collected in two laboratories with identical equipment and setup. Eye movements from eighty-five participants were recorded with two SR Eye-Link I Systems (SMI) operating with a sampling rate of 250 Hz (4-ms temporal resolution). A further 160 participants were tested with two SR Research EyeLink II Systems at a sampling rate of 500 Hz (2-ms temporal resolution). The only significant difference between the two systems is the sampling rate. For saccade detection, the differences in sampling rate were taken into account (see Appendix A). The Eyelink systems have a high spatial resolution (0.005°). Participants were seated 60 or 50 cm in front of the monitor with the head positioned on a chin rest. Thus, at the straight-ahead viewing position letters subtended 0.38° and/or 0.45° of visual angle (center-to-center spacing). Data were collected over several years. For a certain period of time, viewing distance in Laboratory 1 had been changed to 50 cm. Of the 225 readers whose data were analyzed (see Analyses section), 152 were tested at a viewing distance of 60 cm while 73 participants were tested at 50-cm viewing distance.

The Potsdam Sentence Corpus

The Potsdam Sentence Corpus comprises 144 single unrelated German sentences (1138 words). The sentences reflect a variety of grammatical structures in the German language (see Kliegl et al., 2004; Kliegl, Nuthmann, & Engbert, 2006, for details). Sentence lengths range from 5 to 11 words with a mean of 7.9 words.

General procedure

Participants were instructed to read a given sentence for comprehension. In 27% of the trials, the sentence was followed by an easy three-alternative multiple-choice question pertaining to the current sentence. Participants answered the question with a mouse click. The reader initiated the next trial by fixating a target appearing on the centerline of the monitor with a horizontal offset of 66 pixels (relative to the left screen boundary). The sentence was then presented so that the midpoint between the beginning and the center of the first word was positioned at the location of the fixation spot. This was done to ensure that each sentence-initial word was read from a word-specific optimal viewing position. The sentence was displayed until the reader fixated a small black dot placed in the lower right corner of the screen.

Calibration procedure

For calibration, the manufacturer's software was used. Readers' eyes were calibrated with a standard nine-point grid. Participants were instructed to fixate a sequence of nine dots that appeared in random order at the left, center, or right location at the top, middle, or bottom of the screen. Calibration was binocular, i.e., based on both eyes, yet the mathematical models of gaze positions were derived independently for the two eyes. Auto-calibration was used; as a default, the software waits for a 500-ms fixation and uses the last 100 ms (i.e., from 400 ms to 500 ms) to determine the position of the target fixation. Calibration was followed by a 9-point calibration accuracy test. Before each sentence, a black fixation target was presented on the left side of the centerline on the monitor. The participant fixated the target, and the gaze position measured during this fixation was used to correct postcalibration drift errors that might have occurred. Throughout the experiment there was a complete recalibration with the nine-point grid after 11 sentences each. In addition, for any given trial the experimenter was able to view on a separate monitor a box representing the spatial extension of the sentence, overlaid with a cursor corresponding to real-time gaze position. If the experimenter judged that gaze-tracking accuracy had declined, the experimenter initiated an additional full calibration before the next trial. This occurred very infrequently.

In the present study, a binocular calibration procedure was used. There is a view that monocular rather than binocular calibrations should be conducted when studying binocular coordination (Liversedge, White et al., 2006). That means, the left eye is occluded when calibrating the right eye and vice versa. The main argument is that monocular calibration ensures that the position of the eye when viewing a calibration point is based exclusively on the visual input of only that eye (assuming that participants do fixate the calibration point as instructed). While this is a reasonable argument, it does not imply that data obtained under binocular calibration are a priori invalid. A study by Yang and Kapoula (2003) provides relevant information on the subject. In this study, eye calibration was conducted under binocular viewing conditions. The validity of this procedure was established by a previous study showing similar results obtained with calibrations taken under monocular or binocular viewing. In addition, participants' normal binocular vision was verified with the stereoacuity TNO test, indicating that participants were fixating targets with both eyes. Generally, there is no perfect calibration procedure; both monocular and binocular calibrations have drawbacks. Notably, monocular calibration is not ecologically valid as we read with two eyes. On the other hand, the binocular calibration algorithm assumes that the eyes are perfectly aligned on the calibration targets. However, we cannot exclude the possibility that there is some objective binocular disparity when the calibration samples are taken. Therefore, data obtained under binocular calibration might provide a conservative estimate of the *magnitude* of fixation disparity (i.e., the objective magnitude of disparity during the reading task might be somewhat underestimated). There is no reason, however, to expect that it would systematically influence the *direction* of disparity. In any case, some of the analyses reported here were explicitly designed to test the validity of the fixation disparity pattern observed in the present data set. Several systematic effects modulating the observed baseline disparity pattern will be reported. The issue of monocular vs. binocular calibration will be taken up in the Discussion section again.

Analyses

For binocular saccade detection a velocity-based detection algorithm was used (see Appendix A). Sentences containing blinks were removed. As a result, data from 19 readers were excluded from analyses because they contributed less than 100 (out of 144) valid sentences. Data from a further participant were removed because the session was run with a different monitor resolution. No data cleaning or correction procedures were applied; in particular, vertical eye positions were not corrected. If not stated otherwise, first and last fixations in a sentence were excluded. In addition, fixation durations shorter than 50 ms and longer than 750 ms were removed. Given that the fixation disparity might accumulate across the sentence (Heller & Radach, 1999), no outlier removal procedures were applied to fixation disparities. If not stated otherwise, data were collapsed across the two viewing distances. For statistical analyses, means or proportions were calculated for each participant, and these were then averaged across participants. All analysis software was written with MATLAB (The Mathworks). Statistical tests were performed with SPSS and R.

Results

Results will be organized in five main sections. We first introduce the basic pattern of two-dimensional fixation disparities observed in our set of binocular reading fixations. We then provide an in-depth investigation of horizontal disparities, focusing on vergence-related aspects and how the magnitude and direction of disparity change as the eyes move across the sentence. This is followed by investigating the relationship between fixation disparity and the 3-D binocular fixation point. Finally, we discuss how horizontal disparity between the eyes affects spatial measures of eye-movement control in reading.

Horizontal and vertical fixation disparities: Alignment proportions and magnitude of disparity (at the end of fixation)

A binocular fixation consists of two fixation locations, one for the left eye (L_{xy}) and one for the right eye (R_{xy}) while a given fixation location has a horizontal x and a vertical y component. Fixation disparity is defined as the difference between right- and left-eye fixation positions, calculated for the horizontal and vertical dimensions. Consequently, we describe binocular fixations with a two-dimensional disparity D_{xy}, i.e.,

$$D_{xy} = R_{xy} - L_{xy}. \quad (1)$$

The eye trackers' measurement unit is in pixels, which were converted to differences in visual angle between the two eyes. Where appropriate, for the horizontal dimension the visual angle values were further converted to character spaces for ease of discussion. Figure 3a shows a Cartesian coordinate system of horizontal and vertical disparities where each binocular fixation is represented with its two-dimensional disparity value D_{xy} [°]. Disparities were calculated based on fixation position values recorded at the *end* of the fixation, i.e., after any vergence movements were completed. Data points at the origin [0,0] of the coordinate system indicate perfect alignment of the eyes in both dimensions. Negative horizontal disparities signal crossed eyes, i.e., the left eye fixates to the right of the right eye. Negative vertical disparities indicate that the left eye is located above the right eye. Figure 3 indicates that the center of the scatter ball is not at the origin [0,0] of the coordinate system of disparities. Rather, it is shifted toward the left-down. This translates into the following data pattern: Horizontally crossed eyes with the left eye slightly above the right eye is the most frequently occurring case. Apart from that, the disparity data form a "ball" suggesting that there is only a small fixation-based correlation between horizontal and vertical disparities (signed D_{xy}: $r = -0.033$, $p < 0.001$; unsigned D_{xy}, thus taking only the magnitude of disparity into account: $r = 0.093$, $p < 0.001$).

Figure 3b visualizes the two-dimensional frequency information that can be derived from the scatter plot with a contour plot. A contour line (or isoline) for a function of two variables is a curve connecting points where the function has a same particular value. In addition, the proximity of the lines expresses the gradient of the distribution at a given point. Here, the horizontal and vertical disparities follow a Gaussian distribution. Figure 3b displays the corresponding two-dimensional distribution with a contour plot. The

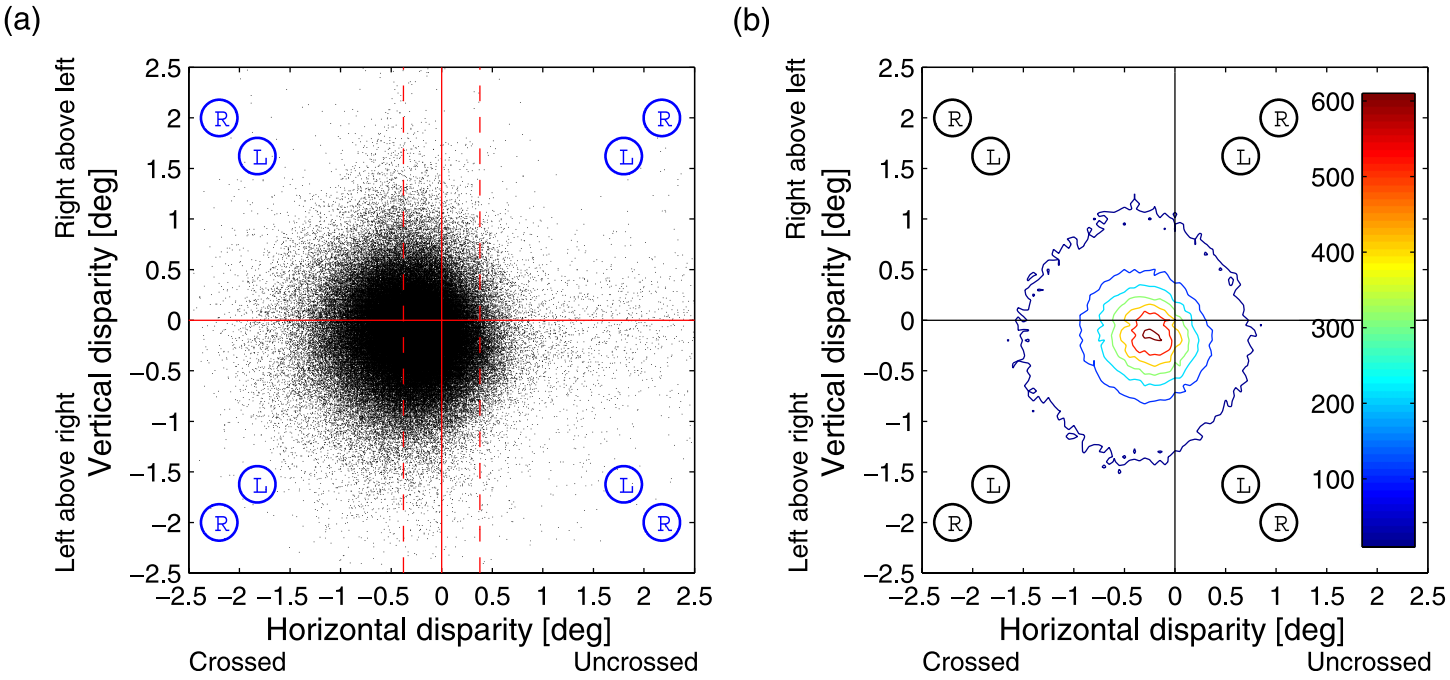

Figure 3. A Cartesian coordinate system of horizontal (x-axis) and vertical (y-axis) disparities of the eyes. For each eye and dimension (horizontal vs. vertical), fixation position values were recorded at the end of fixation. For a given dimension, disparities were calculated as differences between right- and left-eye positions (Equation 1). Thus, positive horizontal disparities signal uncrossed eyes, i.e., the left eye fixates to the left of the right eye. Positive vertical disparities indicate that the right eye is located above the left eye. Data points at the origin [0,0] of the Cartesian coordinate system indicate perfect alignment of the eyes in both dimensions. For a given quadrant, circles with letters "L" and "R" inside visualize the eye pattern. (a) Scatter plot of two-dimensional disparities D_{xy}; each point represents one binocular fixation. Broken vertical lines symbolize the width of a letter in the reading experiment. (b) Corresponding contour plot. Note that frequency information is color-coded. See text for further details.

contour plot was based on a data grid obtained by binning the data points (disparity values) displayed in Figure 3a along the two dimensions with a bin size of 0.05 deg. The frequency information is displayed as 7 level curves. The curves are equidistant, while the frequency distance between two neighboring curves is 100 data points. Taken together, the 7 curves reflect absolute frequencies between 10 and 610, in steps of 100 (see color coding in Figure 3b). The contour plot confirms that the joint distribution peaks at a location shifted to the left-down relative to the origin of the coordinate system.

Horizontal fixation disparities: Alignment proportions

For further numerical evaluation of the data visualized in Figure 3, the binocular fixations were categorized according to the magnitude and direction of fixation disparity. Accordingly, Table 1 provides mean alignment proportions and mean magnitudes of horizontal and vertical disparities (in degrees). For horizontal disparities, the one-letter criterion introduced by Liversedge, White et al. (2006) was used to distinguish aligned and nonaligned (uncrossed vs. crossed) fixation disparities (see above). Fixations were classified as aligned, if the disparity between eyes did not exceed one letter, in either direction. That means, all data points within the two vertical broken lines in Figure 3a represent horizontally aligned binocular fixations.

		∑ Horizontal	Vertical aligned	Vertical right above left	Vertical left above right
Proportions (%)					
∑ Vertical			67.2	9.0	23.8
Horizontal aligned		58.1	40.2	4.5	13.4
Horizontal uncrossed (L R)		3.1	1.9	0.3	0.9
Horizontal crossed (R L)		38.8	25.1	4.2	9.4
Magnitudes (°)					
Horizontal aligned	D_x		0.20	0.20	0.19
	D_y		0.18	0.62	−0.63
Horizontal uncrossed (L R)	D_x		0.54	0.63	0.57
	D_y		0.21	0.79	−0.66
Horizontal crossed (R L)	D_x		−0.65	−0.67	−0.67
	D_y		0.19	0.62	−0.66

Table 1. Joint consideration of horizontal and vertical disparities at the end of fixations. Mean alignment proportions (%) and average magnitudes (°) for horizontal D_x and vertical D_y disparities. Alignment criterion for both dimensions: absolute magnitude of disparity maximal 0.38° (=1 character space in the horizontal dimension). For all conditions involving aligned fixations, mean absolute disparities were calculated, signed means otherwise.

For the present data, the percentage of aligned fixations (58%) is similar to what has been observed in other studies (Blythe et al., 2006; Juhasz et al., 2006; Liversedge, White et al., 2006). However, the results substantially differ from previous research with respect to the proportions of nonaligned fixations. The data indicate that, even at the end of fixation, crossed fixations (38.8%) are much more prevalent than uncrossed fixations (3.1%). Importantly though, analyses of individual data indicate that 13 readers (6%) showed more uncrossed than crossed fixations, suggesting that the present experimental setup generates both overall data patterns. Two movies visualize exemplary fixation sequences, one from a participant showing crossed disparities (Movie 1), and the other one for a reader showing uncrossed disparities (Movie 2).

Vertical fixation disparities: Alignment proportions

To facilitate comparison between horizontal and vertical disparities, the horizontal alignment criterion was also applied to the vertical dimension, i.e., 0.38°, which is the width of a character space. Fixations were categorized into cases where (1) the two eyes were vertically located within 0.38° of each other (aligned fixations), where (2) the two fixations were more than 0.38° apart and the right eye was above the left eye, and where (3) the two eyes were more than 0.38° away while the right eye was below the left eye. These three vertical alignment conditions were crossed with the three horizontal alignment conditions, yielding a 3 × 3 matrix (Table 1).

There appears to be somewhat less fixation disparity in the vertical dimension: Given the chosen alignment criterion, 67% of vertical fixation-position differences between the eyes qualify as aligned fixations, while this is true for 58% of the horizontal disparities only. As for vertical nonalignment, the left eye fixates above the right eye in a quarter of all considered fixations. In addition, the data further substantiate the claim of little systematic relationship between horizontal and vertical disparities. For example, for a given horizontal alignment condition (e.g., crossed eyes), the magnitude of mean horizontal disparity does not vary systematically as a function of vertical alignment condition (e.g., −0.65, −0.67, −0.67°).

The effect of vergence on horizontal fixation disparities

The term "eye fixation" is actually a misnomer, since our eyes are never completely still. Importantly for the present work, the alignment of the fixation points of the two eyes (i.e., binocular disparity) changes during a fixation. Starting point for the following analyses is the observation that vergence movements during reading fixations lead to a reduced disparity at the end of fixation as compared to the start of fixation (Hendriks, 1996; Liversedge, White et al., 2006). First, global analyses

compare the direction and magnitude of horizontal fixation disparities at the *end* of fixation with corresponding data recorded at the *start* of fixation. Such a start–end comparison provides a simple measure of disparity change during fixation (cf., Liversedge, White et al., 2006). We further elaborate on these findings by investigating monocular contributions to intra-fixational vergence, mainly to establish different directional patterns for crossed as opposed to uncrossed fixations. Finally, we go beyond the start–end dichotomy in that we assess how the magnitude of eye disparity changes during the time course of successive saccades and fixations. Based on the findings we then explore whether (and how) fixation disparity accumulates as the eyes move from left to right through a sentence. Note that, overall, the moderate variation in viewing distance (50 vs. 60 cm) had no significant effect on the obtained data patterns. Therefore, data were collapsed across the two viewing distances.

Mean pattern

Table 2 shows the mean proportions of aligned, uncrossed, and crossed fixations for horizontal disparities at the start vs. end of fixation. For a given alignment condition, mean disparity magnitudes are additionally presented. As a technical note: When data were collapsed across alignment conditions and also in case of aligned fixations, magnitude of fixation disparity is reported as unsigned mean difference between eyes ($D_x = |R_x - L_x|$) to ensure that the contributions of positive and negative disparities do not cancel each other out. Several aspects of the present complex data patterns indicate a reduction of binocular disparity during fixation, which is in agreement with previous research (Hendriks, 1996; Liversedge, White et al., 2006). At the beginning of fixation, the mean absolute disparity magnitude was 1.22 (*SE* 0.031) character spaces, while it was reduced to 1.03 (*SE* 0.026) character spaces when recorded at the end of fixations [$t(224) = 15.4$, $p < 0.001$]. From beginning to end of fixation, the proportion of aligned fixations increases from 50% to 58%. This is accompanied by a drop of crossed fixations from 46% to 39% (Table 2). (Note that "∑ End" in Table 2 corresponds to "∑ Horizontal" in Table 1.) A significant proportion of fixations (35%) is crossed both at the beginning as well as the end of fixation, yet the mean disparity magnitude decreases from −1.98 to −1.69 character spaces. The small proportion of uncrossed fixations (3.7%) also shows disparity-reducing behavior: a lot of them become aligned, while for the others we observe an average decrease of disparity magnitude from 1.57 to 1.43 character spaces. We do, however, also observe cases where disparity between the eyes increases during fixation: A small proportion of fixations changes from aligned to either crossed or uncrossed. Note that the end-of-fixation disparity in the order of one letter is close to what has been reported in reading studies with a somewhat different experimental setup (Juhasz et al., 2006; Liversedge, White et al., 2006). This might suggest that the visuo-oculomotor system is self-calibrated at the level of a letter (but see below).

	∑ Start	End aligned	End uncrossed (L R)	End crossed (R L)
Proportions (%)				
∑ End		58.1	3.1	38.8
Start aligned	50.3	45.7	0.9	3.7
Start uncrossed (L R)	3.7	1.5	2.2	0
Start crossed (R L)	46.0	10.9	0	35.1
Magnitudes (char)				
Start aligned	D_{xStart}	0.47	0.60	0.75
	D_{xEnd}	0.43	1.23	−1.22
Start uncrossed (L R)	D_{xStart}	1.31	1.57	–
	D_{xEnd}	0.62	1.43	–
Start crossed (R L)	D_{xStart}	−1.35	–	−1.98
	D_{xEnd}	0.71	–	−1.69

Table 2. Horizontal disparities at the start vs. end of fixation. Fixations were categorized as aligned, crossed, or uncrossed (see text for details). Alignment criterion was one character space. Presented are mean alignment proportions (%) and magnitudes of disparities, expressed in character spaces (absolute means for all conditions involving aligned fixations, signed means otherwise).

Monocular contributions to vergence differ for crossed and uncrossed fixation disparities

The following analyses consider the independent contributions of the two eyes to vergence. The main goal is to test the validity of the observed crossed–uncrossed fixation disparity pattern. Could the dominance of crossed over uncrossed fixation disparities be an artifact of the eye-tracking system and binocular calibration? Such an assumption implies that a significant proportion of the observed crossed disparities are not true crossed disparities. We can counter this argument in that we (1) identify circumstances where crossed and uncrossed fixations should differ in their oculomotor response and (2) demonstrate that our data show the predicted dissociation. In contrast, we formulate the following null hypothesis: If the data do not show the predicted dissociation, the measured disparities might not represent true fixation disparities. Starting point for our demonstration is the undisputed finding that disparity reduction throughout fixation is achieved by vergence movements of the eyes (Hendriks, 1996; Liversedge, White et al., 2006). For rejection of the null hypothesis, we should observe a *dissociation* for crossed and uncrossed fixations: Initially uncrossed fixations should show convergence while initially crossed fixations should show divergence. Figure 2 gives an example. For two binocular fixations, the lines of sight

are plotted, i.e., the visual lines through the respective point of fixation on the screen of text and the centers of rotation of each eye. The right-hand fixation shows uncrossed disparity. In order to reduce disparity, both eyes would need to move inward, i.e., toward each other (convergence). The left-hand fixation shows crossed disparity. Here, disparity reduction is actually achieved by divergence: The left eye would need to move to the left while the right eye would need to move to the right, which corresponds to outward (abducting) movements of both eyes. (Of course, disparity reduction can also be achieved by movement of one eye only.)

These hypotheses were tested by analyzing monocular eye-position values. For a given fixation, the difference between the absolute horizontal fixation position at the end and start of fixation was calculated. This was done for each eye separately. The obtained difference values are an indicator of monocular movements during fixation. For the two eyes, Figure 4 depicts the resulting distributions of difference values, separately calculated for crossed (Figure 4a) vs. uncrossed (Figure 4b) fixations. Positive values indicate that at the end of fixation, the eye was positioned further to the right as compared to the start-of-fixation position values. Distributions are based on a bin size of four min arc. Note that distributions for uncrossed fixation disparities are based on a much smaller number of fixations (cf., Table 2).

The results show the predicted dissociation. For crossed fixations (Figure 4a), the distribution for the right eye is shifted to the right, indicating abducting movements. A right-tailed *t*-test indicated that the mean difference value (M = 5.74 min arc, SE = 0.340) was significantly greater than zero [$t(224)$ = 16.9, $p < 0.001$]. The left-eye distribution, however, is shifted to the left [M = −3.84 min arc, SE = 0.270; $t(224)$ = −14.2, $p < 0.001$]. Taken together, the pattern for crossed fixations is indicative of divergence (i.e., outward rotation of the eyes). Uncrossed fixations show the opposite pattern (Figure 4b). The left eye has a preference for rightward movements, which means adduction [M = 4.52 min arc, SE = 0.486; $t(213)$ = 9.1, $p < 0.001$].[2] The right-eye distribution is shifted to the left [M = −7.72 min arc, SE = 0.605; $t(213)$ = −12.4, $p < 0.001$]. In sum, the pattern for uncrossed fixations translates into an inward rotation of both eyes (convergence).

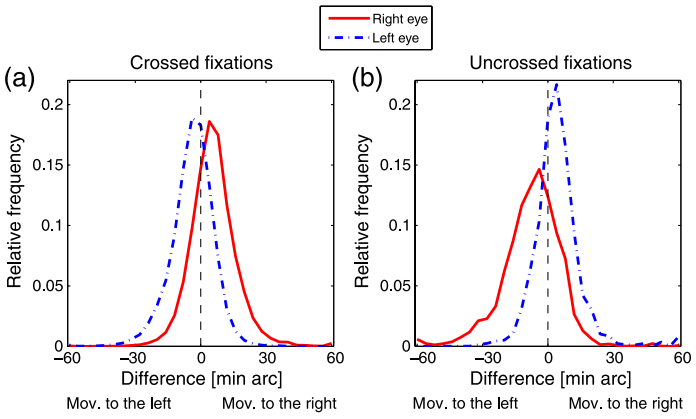

Figure 4. Distribution of changes in monocular fixation position from start to end of fixation. Data from the right eye (solid line) are contrasted with data from the left eye (broken line). For a given fixation, the difference between the absolute horizontal fixation position at the end and start of fixation was calculated. This was done for each eye separately. Positive values indicate movements to the right. Panels contrast data for initially crossed (a) vs. uncrossed (b) fixation disparities.

To summarize, the relative contributions of the two eyes to vergence show different directional patterns for crossed and uncrossed fixations (divergence vs. convergence). The present findings will be further elucidated by a theoretical analysis of the two hypothetical lines of sight forming the vergence angle γ (see below). Importantly, the observed dissociation also suggests that observing a dominance of crossed disparities is likely not to be an artifact of a binocular calibration procedure. If the observed pattern of crossed and uncrossed disparities was distorted by the measurement procedure, there is no reason why such dissociation should have been observed.

We can further strengthen our argument by showing that a linear transformation of the data destroys the dissociation. The majority of our data shows a negative disparity with the left eye fixating ahead of the right eye. We can alter this pattern with a simple linear transformation: For each binocular fixation, the fixation position for the *right* eye (only) is rightward shifted by 1 letter, $R'_x = R_x + 1$ (cf., Equation 1). This is done for right-eye fixation positions both at the start and end of fixation. One letter was chosen because it represents the mean absolute end-of-fixation disparity in our data. The resulting fixation disparity ball (cf., Figure 3) is now shifted to the right, toward more aligned and more uncrossed fixations (see Supplementary material). Due to the nature of the transformation, all fixations that are now assigned a negative disparity did also show a negative disparity without the transformation. This is why the analysis of monocular contributions to vergence still shows the directional pattern depicted in Figure 4a ($p < 0.001$). Importantly, however, the original pattern for the now positive disparities cannot be established any longer ($p > 0.05$). Thus, these fixations do not behave like uncrossed fixations, indicating that the transformation created uncrossed fixations that are not uncrossed in nature.

We are aware that the applied measurement system produces noise, i.e., not every single crossed fixation disparity might represent a true crossed fixation disparity (uncrossed fixations, respectively). However, the large number of data collected here reduces the noise sufficiently.

In sum, the analyses presented in Figure 4 validated the observed crossed–uncrossed fixation disparity pattern. In addition, they are informative on the issue whether the

two eyes contribute equally (or symmetrical) to intra-fixational vergence. The above analyses of monocular changes in eye positions indicate a higher monocular activity of the right eye as compared to the left eye (see also Hendriks, 1996). Compared with the left eye, the right-eye data show greater standard deviations and greater deviations from 0. This was observed for both crossed and uncrossed fixation disparities, which renders it unlikely that the asymmetry is due to the leading eye. We conclude that the relative contributions of the two eyes to intra-fixational vergence in reading appear to be asymmetric (cf., Enright, 1998, for a nonreading task requiring saccades to a target in space).

How does the magnitude of eye disparity change during the time course of a fixation and incoming/outgoing saccade?

Comparing the data from the beginnings and ends of fixations, as has been done in the previous two sections, provides a simple measure of disparity change during fixation. Such an analysis is based on two snapshots and thus ignores the dynamics of eye-movement behavior during fixation. Therefore, the present analysis investigates how the magnitude of eye disparity changes during the time course of a fixation and incoming/outgoing saccade. (We note that this is still a highly aggregated reflection of the dynamics of fixational eye movements.) Research employing nonreading tasks has shown that the eyes tend to diverge during the first, accelerating phase of the saccade and converge during the following decelerating phase. The remaining fixation "error" at saccade offset is further reduced by post-saccadic convergence (Collewijn et al., 1988a; Zee et al., 1992). For reading, it has been shown that the eyes converge during fixations while vergence velocity decreases over time (Hendriks, 1996). In contrast, there is an anecdotal report of relatively uniform convergence movements during fixation, with a velocity of about 1°/s (Heller & Radach, 1999). Vergence movements in reading are considerably slower than in scanning data, mainly due to differences in saccade sizes (Hendriks, 1996). The question remains whether successive saccades and fixations in reading also show the divergence–convergence pattern established for simple scanning tasks and how that relates to the disparity between eyes. For one exemplary gaze trace from the present reading study, Figure 1a shows the disconjugacy (vergence) trace displayed at a high-resolution scale. Even at the level of a single gaze trace it is evident that the eyes move away from each other during saccades but tend to move toward each other in fixation, while the latter is more pronounced toward the end of a sentence (see below). For the present data set, we systematically analyzed how the magnitude of eye disparity changes during the time course of a fixation (Figures 5b and 5c) and saccade (Figures 5a and 5d). Note that fixations and saccades show a considerable variance in duration. Therefore, the development of disparity magnitude was calculated both relative to the *onset* of fixation (Figure 5b) or saccade (Figure 5d), as well as relative to the *offset* of fixations (Figure 5c) and saccades (Figure 5a). Such an average procedure requires window sizes that are somewhat larger than the average fixation and saccade duration observed in reading (fixation duration: ca. 200 ms, saccade duration: ca. 30 ms). Consequently, the analysis window spanned 300 ms for fixation-locked averaging, and 40 ms for saccade-related averaging. The bin width for averaging was 4 ms, according to the minimum sampling rate of recordings in the present study (250 ms). For example, fixation-locked averaging was based on 195,277 (binocular fixations) × 75 (binocular fixation positions at time *t*) data points. Data were not smoothed. Data were collapsed across alignment conditions; consequently, unsigned mean magnitude of disparity is reported.

Implications for saccade data require combined consideration of saccade-onset and saccade-offset locked data. The saccade-onset locked data (Figure 5d) suggest that in the first, accelerating phase of a reading saccade, the eyes move away from each other. However, during the following decelerating phase of the saccade the eyes move toward each other again, as reflected by the saccade-offset locked curve (Figure 5a). The fixation data confirm that this vergence behavior continues into the fixation period following the incoming saccade. After a period of 150–200 ms, however, the fixation-onset locked curve levels off. This is further corroborated by the corresponding velocity profile (inset plot in Figure 5b), indicating that vergence velocity steadily decreases over time. The two fixation curves complement each other almost perfectly: Looking forward into the fixation provides the same information content as looking back from fixation offset (Figure 5c). In contrast, the onset- and offset-locked average curves for saccades show highly complementary but differing information. This can be explained by the natural variation in saccade amplitude and duration in reading, taking into account that amplitude and velocity of the intra-saccadic divergence–vergence sequence vary as a function of saccade amplitude (Collewijn et al., 1995). In sum, the vergence movements observed during the time course of saccades and fixations in reading replicate the qualitative data pattern observed in nonreading tasks (Collewijn et al., 1988a; Zee et al., 1992). Given the prevalence of crossed fixation disparities in the present data set, however, the mean pattern is of opposite direction, i.e., it is a convergence–divergence sequence rather than a divergence–convergence sequence.[3] In terms of eye disparities, what we observe is a sequence of eye disparity increase–reduction across successive saccades and fixations. Two straightforward disparity-related hypotheses can be derived. First, the disparity *increase* from start to end of a *saccade* should increase with the length of the saccade (Collewijn et al., 1995). A linear

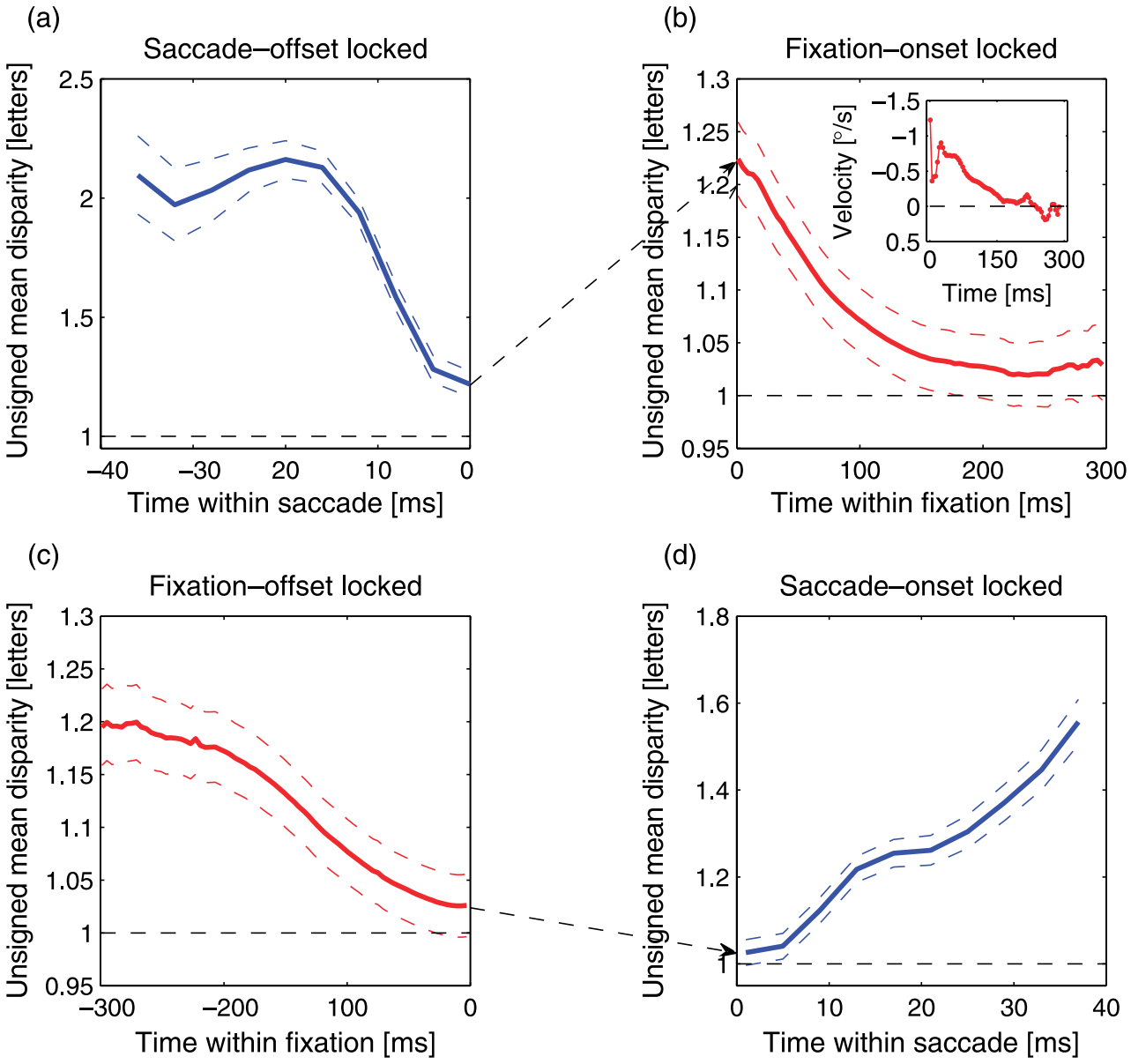

Figure 5. Change of disparity magnitude during the time course of reading fixation (b and c) and incoming (a) or outgoing (d) saccade. The development of disparity magnitude was calculated both relative to the *onset* of fixation (b) and saccade (d), as well as relative to the *offset* of fixations (c) and saccades (a). Note that the saccade offset of the incoming saccade is immediately followed by fixation onset. Therefore, disparities at time $t = 0$ in (a) and (b) coincide (see arrow). Likewise, fixation offset is immediately followed by saccade onset of the outgoing saccade. Consequently, disparities at time $t = 0$ in (c) and (d) match up as well (see arrow). Note that scaling of the *y*-axis differs across panels. Broken-line bands around the averaged curve represent error bars (±1 *SE*). Broken horizontal lines mark one-letter fixation disparity. For (b) fixation-onset locked averaging, the inset plot shows the corresponding vergence velocity profile; negative velocities indicate that the eyes move towards each other.

model with saccade length as predictor and mean unsigned change of disparity from start to end of saccade, $|D_{x\mathrm{End}}| - |D_{x\mathrm{Start}}|$, as dependent variable was specified. Given that saccade lengths for the two eyes slightly differ (see below), the conjugate signal $[(L + R)/2]$ was used. Indeed, the greater the amplitude of the saccade, the more eye disparity remained at the end of the saccade [intercept = 0.28 char, $b = 0.11$ char, $t = 71.06$, $p < 0.001$]. Second, the disparity *reduction* from start to end of a *fixation*, $|D_{x\mathrm{Start}}| - |D_{x\mathrm{End}}|$, should increase with fixation duration (cf., Liversedge, White et al., 2006), and this is what was found [intercept = 0.19 char, $b = 0.043$ char, $t = 28.0$, $p < 0.001$]. Finally, note that long saccades are followed by long fixations (Kliegl et al., 2006).

How does the magnitude and direction of fixation disparity change as the eyes move from left to right through a sentence, and how is that modulated by intra-fixational vergence?

In the previous section we established a sequence of eye disparity increase–reduction during the course of saccades and successive fixations. During fixation, saccade-induced eye disparity is reduced but typically not completely removed. Therefore, the remaining fixation disparity might accumulate across the sentence (Heller & Radach, 1999). Specifically, across several fixations, the disparity observed at the start of fixation should systematically increase. This is counteracted by fixational vergence, while this could happen in different ways. First, let us assume that the accumulated start-of-fixation disparities get so large that they threaten to compromise single binocular vision. In this case, we expect the vergence system to counteract by *increasing* the net disparity reduction throughout fixation as the eyes move from left to right through a sentence (i.e., end-of-fixation disparities would increase to a lesser degree than start-of-fixation disparities). Alternatively, across fixations net disparity reduction throughout fixation might simply be a constant, so that end-of-fixation disparities would increase to the same extent as the start-of-fixation disparities.

For testing the hypothesis of a possible disparity accumulation, fixation disparity was calculated as a function of ordinal number of fixation on the line of text. Distances between successive fixations in Figure 6 are scaled according to the mean horizontal position of the respective fixation on the screen. Note that the mean endpoint of sentences, relative to the left border of the screen, was at 56 letters. Analyses were restricted to forward saccade sequences only; i.e., whenever there was a regression (i.e., a right-to-left movement along the line) in the trial, fixations were excluded as of the (first) regressive movement. To investigate how net disparity reduction during fixation develops across the sentence, we compared disparities recorded at the start of fixation with disparities as observed at the end of fixation. The difference yields the net disparity reduction from start to end of fixation. For comparison, we additionally analyzed disparities obtained by averaging position values across fixation. Furthermore, the right *y*-axis in Figure 6a displays mean fixation duration measured for the left and right eyes, as a function of fixation number. For exploratory reasons, analyses included the first fixation in the sentence, which was otherwise routinely excluded from all analyses (see Analyses section).

For didactic reasons, we start with the fixation duration data (bottom lines in Figure 6a). In the experiment, the sentence was presented after the reader fixated an initial fixation point on the screen (indicated by the leftmost broken vertical line in Figure 6). On average, this first fixation lasted longer than the other fixations, resulting into more parafoveal processing of the upcoming word, which in turn leads to a reduced fixation duration for the second fixation (Figure 6a). Leaving the first and second fixations within a sentence aside, the data indicate a small but systematic increase in fixation duration across the line of text (Figure 6a, right *y*-axis; for statistics see below). The correlation between fixation durations from the left vs. right eye is almost perfect ($r = 0.997$, $p = 1$).

We now turn to the magnitude of disparity data. Start-of-fixation disparity data demonstrate that there is a steady accumulation of the mean fixation disparity across fixations up to an average value of about 1.52 (SE = 0.054) letters (Figure 6a). End-of-fixation disparities also increase across the sentence, but not as much as the start-of-fixation disparities. This implies that the net disparity reduction throughout fixation (i.e., the shaded area in Figure 6a) increases as the eyes move from left to right through a sentence. Taken together, the data pattern suggests that the visuo-oculomotor system tolerates the accumulation of fixation disparity only to a certain degree. Finally, the curve based on fixation position values that were averaged across the whole fixation (Figure 6a, dotted line) is closer to the curve reflecting end-of-fixation disparities than the start-of-fixation curve, confirming the observation that vergence movements predominantly take place early in the fixation (see previous section). Data presented here were collapsed across alignment conditions. Separate analyses for the three alignment conditions can be summarized as follows: First, for aligned fixations the magnitude of disparity did not vary much across the sentence. Second, due to the small number of uncrossed fixation disparities, computed curves were unstable and thus inconclusive. How do the present data compare to previously reported results? Comparison data are available only for end-of-fixation disparities (Liversedge, White et al., 2006) or for disparities at 150 ms following fixation onset (Heller & Radach, 1999), but note that both reference studies lack statistical evaluation of the data. (Further, Liversedge et al. used the binned letter position on the line of text as independent variable.) The present data clearly differ from Liversedge et al.'s observation of no systematic change of end-of-fixation disparity magnitude throughout the sentence. Rather, they are in agreement with what Heller and Radach (1999) showed for the first line of multi-line text.

We now turn to a statistical evaluation of the fixation disparity accumulation hypothesis. Analyses considered the net disparity reduction from start to end of fixation as dependent variable, calculated as $|D_{x\mathrm{Start}}| - |D_{x\mathrm{End}}|$. The predictor ordinal fixation number represents the accumulated aspects of eye disparity. Owing to the results from the previous section, the incoming saccade length and fixation duration were included as further predictors. To test the effect of these predictors simultaneously, a linear mixed-effects model was specified. The three predictors and their interactions were included as fixed

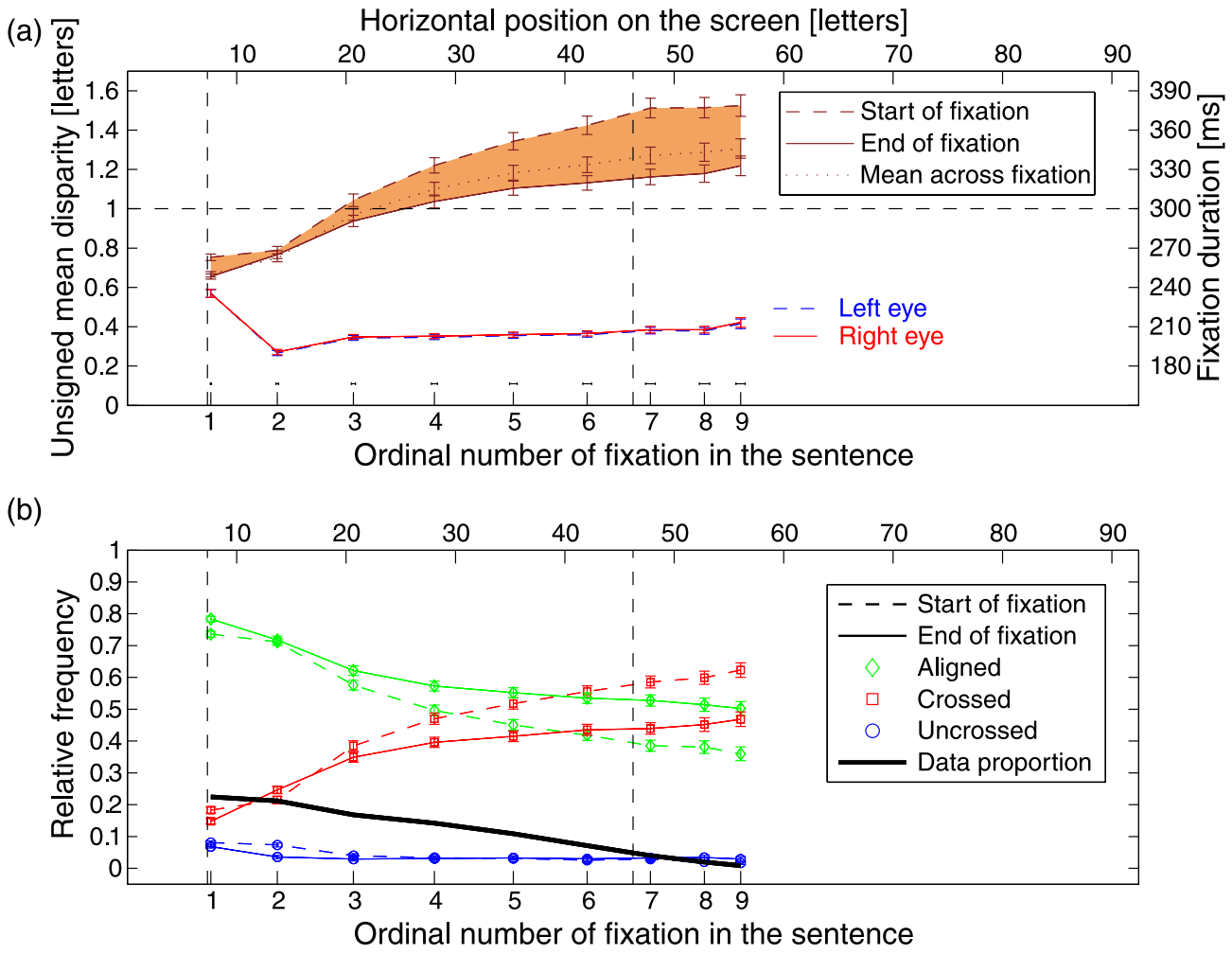

Figure 6. (a) Mean unsigned magnitude of fixation disparity as a function of the ordinal number of the fixation on the line of text. Data recorded at the start of fixation (broken line) are contrasted with data from the end of fixation (solid line). For comparison, disparities obtained by averaging position values across fixation are additionally presented (dotted line). Error bars are ±1 *SE*. The lower *x*-axis represents the ordinal number of the fixation on the line of text. Here, distances are scaled according to the mean horizontal position of the respective fixation on the screen; horizontal error bars are ±1 *SE*. Accordingly, the upper *x*-axis represents the letter position on the screen, relative to the left border of the screen [0 letters]. In addition, the right *y*-axis depicts mean fixation duration for the left vs. right eye as a function of ordinal fixation number. The horizontal broken line marks a one-letter mean unsigned disparity magnitude. (b) Proportion of aligned, crossed, and uncrossed horizontal fixation disparities as recorded at the start vs. end of fixation, determined as a function of the ordinal number of the fixation on the line of text. The proportion of data that contributed to each fixation number (thick black line) is additionally presented. In both panels, vertical broken lines indicate (1) the location of the initial fixation checkpoint and (2) the center of the screen.

effects while participants were treated as random effects (i.e., individual differences in the intercept were taken into account). Predictors were centered (Baayen, 2008). Analyses were performed with the *lmer* program (lme4 package, Bates, 2007) in the *R* system for statistical computing (R Development Core Team, 2008). *p* values were obtained by using Markov chain Monte Carlo sampling (cf., Baayen, 2008, for discussion). The model was applied to the nonaggregated sequence of binocular fixations. Given that data for fixations 1 and 2 were affected by the experimental setup, analyses were restricted to data representing fixations 3 to 9. First, we consider the correlational structure of the predictors. Higher fixation numbers are associated with shorter saccade lengths ($r = -0.12$, $p < 0.001$)[4] but somewhat longer fixation durations ($r = 0.03$, $p < 0.001$). Besides, there is a positive correlation between saccade length and subsequent fixation duration ($r = 0.13$, $p < 0.001$). The intercept, representing mean net disparity reduction, was estimated as $b = 0.257$ char ($t = 18.06$, $p < 0.001$). Fixation number ($b = 0.048$ char, $t = 51.17$, $p < 0.001$), incoming saccade length ($b = 0.11$ char, $t = 52.53$, $p < 0.001$), and fixation duration ($b = 0.026$ char, $t = 14.52$, $p < 0.001$) showed significant main effects on net disparity reduction. Most notably, the net disparity reduction increases with fixation number. Besides, longer incoming

saccade lengths are followed by more disparity reduction throughout fixation (main effect of saccade length) while this is even more pronounced for higher fixation numbers, that is, in cases of increased start-of-fixation disparity (interaction saccade length × fixation number: $b = 0.015$ char, $t = 15.65$, $p < 0.001$). Following longer incoming saccade lengths, there is a stronger disparity-reducing effect of fixation duration (interaction saccade length × fixation duration: $b = 0.008$ char, $t = 4.48$, $p < 0.001$). The fixation number × fixation duration interaction and the 3-way interaction were not significant. Taken together, the data support the fixation disparity accumulation hypothesis outlined above.

Eventually, significant changes in the magnitude of disparity must translate into changes in types of alignment. This is visualized in Figure 6b showing how the proportions of aligned, crossed, and uncrossed fixation disparities develop across the sentence. At the initial fixation point, the majority but not all fixations (i.e., about 80%) were aligned. This changed systematically as the eyes moved from left to right across the line of text: Due to disparity accumulation (Figure 6a), the proportion of aligned fixation decreases. This is mostly counterbalanced by an increased proportion of crossed fixation disparities. Note that these findings differ from previously reported results where aligned fixation disparities peaked at screen center while proportions of crossed fixations were increased at the left and right extremes of the screen (Liversedge, White et al., 2006). Two findings arise from the comparison of proportions at start vs. end of fixation. Generally, when disparity is measured at the end as compared to the start of fixation, more fixations are aligned and less fixations show crossed disparity (cf., Table 2). In addition, throughout the sentence the magnitude of change in alignment type from start to end of fixation increases (Figure 6b), due to the increased net disparity reduction (Figure 6a).

Interim summary

To summarize the sections on horizontal fixation disparities, the present data differ from previously reported data in that they show a dominance of crossed (rather than uncrossed) fixations. Furthermore, the data suggest that the version and vergence system in reading do not operate independently but strongly interact, qualitatively in a similar way as observed in simple nonreading tasks (e.g., Collewijn et al., 1988a, 1997). In particular, the eyes move away from each other during the initial accelerating stage of the saccade. During the second decelerating stage of the saccade, the eyes move toward each other again while this vergence behavior continues into the early stage of fixation. Consequently, unsigned mean magnitude of fixation disparity is reduced at the end of fixation as compared to the start of fixation (Liversedge, White et al., 2006; but see Blythe et al., 2006). Monocular contributions to intra-fixational vergence appear to be asymmetric and show different directional patterns for crossed vs. uncrossed fixation disparities. Finally, as the eyes move from left to right through a sentence, the start-to-end of fixation net disparity reduction increases, probably to maintain single binocular vision.

An investigation of the binocular fixation point

The present data markedly differ from previously reported data in that they show a prevalence of negative fixation disparities. Therefore, a penultimate set of analyses aimed at better understanding the differences between positive and negative fixation disparities. What are the implications of crossed as opposed to uncrossed fixation disparities with respect to vergence control? Here, we revisit the data from a different perspective. This new perspective explicitly takes the geometrical arrangement between the centers of the two eyes and the fixated object into account. Such an approach accords with the view commonly adopted in basic oculomotor research. Instead of quantifying the data in terms of magnitudes of fixation disparity in character spaces, we now use the vergence angle as our main unit of reference. To reiterate, the lines of sight of the two eyes intersect at the binocular fixation point I_{xyz}, forming the vergence angle γ (Figure 2, Movies 1 and 2). The subsequent set of analyses explores the following questions: What are the interrelations between the binocular fixation point and the vergence angle as well as the direction and magnitude of fixation disparity, and how can we quantify the modulating influence of vergence movements? There is a nonlinear relation between viewing distance and vergence angle (Collewijn et al., 1997). Therefore, given that viewing distance in the present study varied between 50 and 60 cm, analyses included viewing distance as another independent variable. The effect of vergence was taken into account by contrasting data recorded at the start vs. end of fixations. Analyses were based on three somewhat simplifying assumptions. First, it was assumed that participants' straight-ahead view was at the midpoint of the screen. The experimental setup in the present study met this requirement with sufficient approximation. In the experiment, table height could be adjusted according to the body height of the reader, assuring that the sentence was presented in a horizontal plane at about eye level. The chin rest was placed such that the reader's midpoint between the centers of the eyes was close to the vertical midline of the screen. Second, given that individual data for participants' inter-ocular distance were not available, analyses were based on an average value of 65 mm (cf., Collewijn et al., 1997). The third assumption relates to the numerical determination of the binocular fixation point. A unique binocular fixation point only exists if the vertical elevation of both eyes is equal (iso-elevation) (cf., Movies 1 and 2 for visualization). An exploratory analysis of vertical disparities suggested that in the majority of cases this

condition was not met (see above). For these instances, the binocular fixation point was operationally defined as the site of shortest distance between the two lines of sight (see Appendix A for details).

To establish a baseline for what follows, a set of geometrical calculations investigated how the vergence angle γ would change across the line of text. The experimental setup imposed the following boundary conditions: (1) straight-ahead view was at the midpoint of the screen, (2) the sentence start point was close to the left border of the screen, and (3) straight-ahead viewing distance was 50 or 60 cm. Simulations were based on iso-elevation of the eyes and a constant absolute horizontal fixation disparity of 1 letter (i.e., the mean end-of-fixation disparity observed in our data), either in positive (uncrossed) or negative (crossed) direction, comparing both viewing distances (Figure 7a). The virtual eyes moved across the hypothetical line of text in steps of one pixel. Results are plotted as a function of the horizontal component of the binocular fixation point (I_x, cf., Figure 2). They can be summarized as follows: Geometrical relations indicate that γ is largest for binocular fixation close to the median plane (the median plane is the plane perpendicular to the inter-ocular axis), i.e., when convergence is symmetrical. The further the to-be-fixated object deviates from the median plane, the smaller is the vergence angle the eyes need to adopt. In addition, crossed fixation disparities are associated with larger angles than uncrossed fixation disparities (see below). Furthermore, closer viewing distances lead to larger vergence angles.

The simulated data provided a baseline condition assuming a constant magnitude of disparity. In a next step, we analyzed the vergence angles that were estimated from the empirical data (Figure 7b). The empirical binocular fixation position data deviate from the simulated data in that they indicate considerable variation in the magnitude of horizontal disparities (see above). In a first analysis, the mean vergence angle was calculated as a function of alignment condition (applying the one-letter alignment criterion) and viewing distance, further contrasting start- and end-of-fixation values. First, the level of means is compatible with the geometrical predictions. Second, we compare means obtained at start vs. end of fixation to validate our findings on disparity-driven vergence movements of the eyes. In previous analyses, we established a divergence–convergence dissociation for crossed and uncrossed fixation disparities (Figure 4). We now extend the underlying logic by taking the actual vergence angle γ into account. Reducing the magnitude of a fixation disparity that is initially crossed requires divergence and thus adoption of a smaller vergence angle. In contrast, in order to reduce the magnitude of an initially uncrossed fixation disparity, the eyes need to adopt a larger γ (convergence). To test this hypothesis, we compared means obtained at start vs. end of fixation (Figure 7b). The data are in agreement with the predictions, as confirmed by repeated measures ANOVAs coding vergence (start vs. end of fixation) as 2-level factor [viewing distance 60 cm, crossed disparities: $F(1,151) = 9.2$, $MSe = 0.005$, $p < 0.001$, uncrossed disparities: $F(1,151) = 2.3$, $MSe = 0.014$, $p < 0.001$; viewing distance 50 cm, crossed disparities: $F(1,72) = 9.1$, $MSe = 0.007$, $p < 0.001$, uncrossed disparities: $F(1,72) = 2.6$, $MSe = 0.019$, $p < 0.001$].

Furthermore, previous analyses indicated that the net disparity reduction throughout fixation increases as the eyes move from left to right through a sentence (shaded area in Figure 6a). Consequently, the mean unsigned change in γ from start to end of fixation should increase as a function of ordinal number of the fixation on the line of text, and this is exactly what was found (Figure 7c); statistical significance was confirmed by a repeated measures ANOVA with fixation number as factor [$F(8,224) = 7.39$, $MSe = 0.004$, $p < 0.001$].

If the binocular fixation point is precisely on the plane of text ($I_y = 0$), the binocular eye movement records will indicate perfectly aligned fixations ($D_x = 0$). Most binocular fixations are, however, disparate and the corresponding binocular fixation point thus deviates from the plane of text. The aim of the next analysis was to quantify this deviation. For uncrossed fixations, the binocular fixation point is behind the monitor, while it is in front of the monitor for crossed fixations (cf., Figure 2).[5] Interestingly, the distribution of I_y follows a Gaussian distribution, while the uncrossed fixations form the right tail of the distribution (Figure 7d). Given that we observe more negative than positive horizontal fixation disparities (Figure 3), the distribution of I_y peaks slightly in front of the monitor (negative I_y, end-of-fixation disparities: $M = -2.6$ cm, $SE = -0.14$ cm). Figure 7d depicts separate distributions for the two viewing distances. The inset plot displays corresponding means as a function of viewing distance and, additionally, start- vs. end-of-fixation disparity. Data were subjected to a 2 × 2 mixed ANOVA with vergence (start vs. end of fixation) as within-participant factor and viewing distance (50 vs. 60 cm) as between-participant factor. The main effect of vergence was significant [$F(1,223) = 84.50$, $MSe = 0.27$, $p < 0.001$], and so was the main effect of viewing distance [$F(1,223) = 8.74$, $MSe = 8.93$, $p = 0.003$]. There was no significant interaction [$F(1,223) = 1.62$, $MSe = 0.436$, $p = 0.205$]. A further analysis investigates the relationship between I_y, γ, and viewing distance in a scatter plot where each data point represents one binocular reading fixation (Figure 7e). The data confirm that crossed fixations (red dots) are associated with larger vergence angles. The eye muscles controlling the focusing lens contract and shorten. As a result, the lines of sight of the eyes intersect in front of the monitor (negative I_y). On the other hand, uncrossed fixations (blue dots) show smaller vergence angles and the binocular fixation point is located beyond the monitor (positive I_y). Interestingly, the relationship between γ and I_y is nonlinear. Again, given that closer viewing distances are associated with larger vergence angles, the right

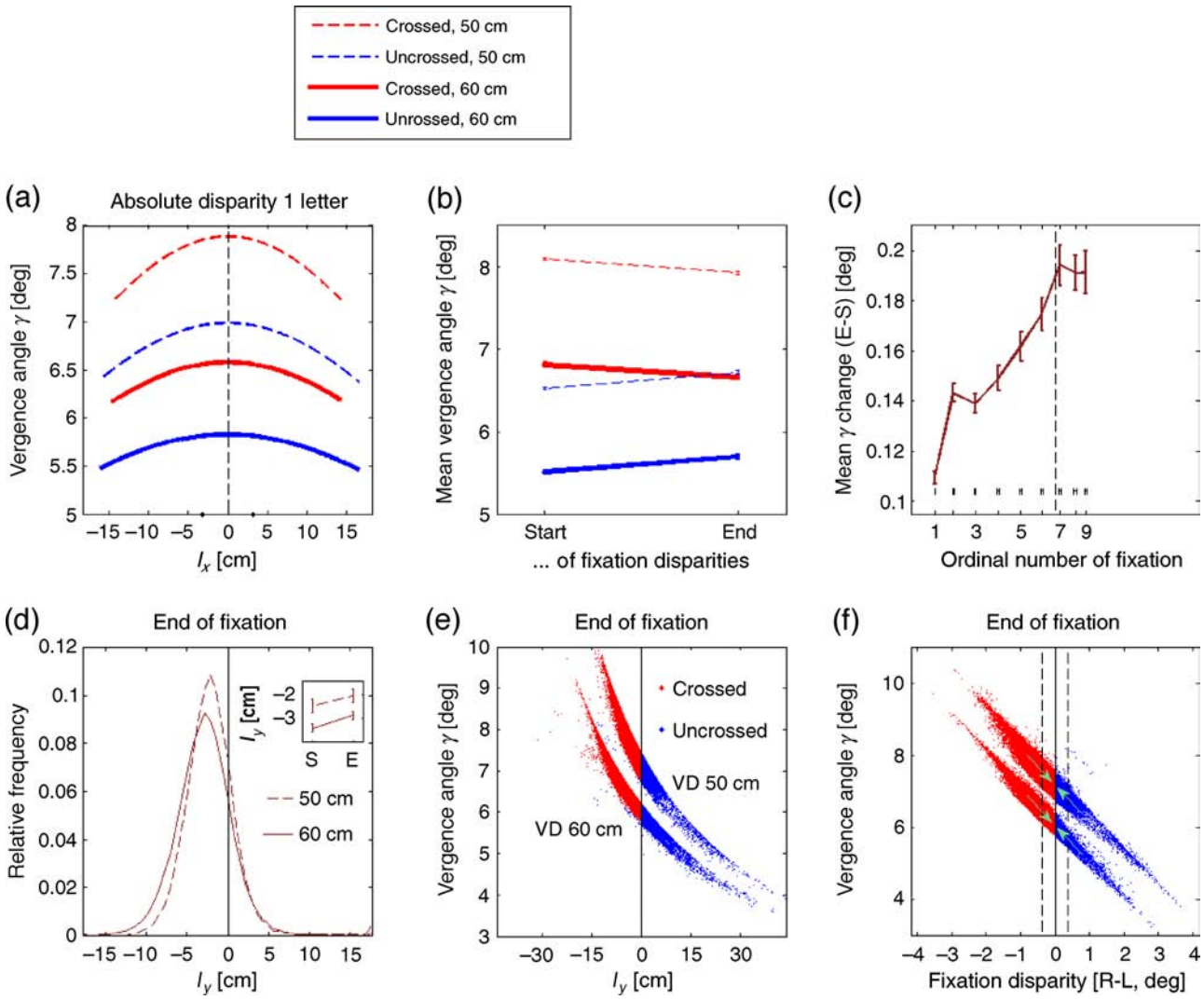

Figure 7. Investigation of the lines of sight which intersect at the binocular fixation point I_{xyz} and form the vergence angle γ (cf., Figure 2). Note that the lines of sight can be only approximately determined. (a) Based on a constant absolute fixation disparity of 1 letter, the size of γ [°] is simulated as a function of I_x, for positive (uncrossed) and negative (crossed) fixation disparity and for viewing distances of 50 and 60 cm. (b) Empirical mean vergence angle γ [°] at start vs. end of fixation, as a function of alignment condition (crossed vs. uncrossed) and viewing distance (50 vs. 60 cm). (c) Mean unsigned change in γ from start to end of fixation, as a function of ordinal number of the fixation on the line of text. (d) Distribution of the binocular fixation point's distance to the surface of the monitor (0 cm), as a function of viewing distance for end-of-fixation data. The binocular fixation point is located either in front of the monitor (negative I_y, crossed fixations) or beyond the monitor (positive I_y, uncrossed fixations). The inset plot displays corresponding means as a function of viewing distance and, additionally, start- vs. end-of-fixation disparity. (e) Relationship between vergence angle γ [°] and I_y [cm]. (f) Relationship between vergence angle γ [°] and magnitude of fixation disparity [°]. Broken vertical lines symbolize the width of a letter in the experiment. In both scatter plots, each data point characterizes one binocular eye fixation; red dots represent crossed fixations. Both scatter plots depict end-of-fixation data. See text for further details.

sickle-shaped data cluster reflects eye fixations recorded at a viewing distance of 50 cm, the left one 60 cm. Finally, there is a linear relationship between fixation disparity and vergence angle γ (Figure 7f): With increasing absolute magnitude of disparity, the vergence angle becomes larger (crossed fixations) and/or smaller (uncrossed fixations). At the same time, the binocular fixation point moves further away from the monitor surface (Figure 7e). Reversely, the relation between disparity reduction and vergence can be specified as follows. In case of initially crossed fixations, disparity reduction is achieved by divergence: A smaller vergence angle is adopted (Figure 7f) and the binocular fixation point thus moves further away, toward the screen (Figure 7d). In contrast, initially uncrossed fixations show typical convergence movements: The eyes adopt a larger apex angle (Figure 7b). Consequently, at the end of fixation the binocular fixation point is located closer to the subject but also closer to the plane of text on the screen

(Figure 7e). Taken together, disparity reduction always makes the binocular fixation point gravitate toward the plane of text (see arrows in Figure 7f). Furthermore, both scatter plots visualize a minimum γ for crossed fixation disparities and a maximum γ for uncrossed disparities. Thus, we can describe crossed and uncrossed fixation disparities as conditions of over- and under-convergence.

How does horizontal fixation disparity affect measures of eye-movement control in reading?

The previous analyses considered basic aspects of binocular coordination in reading. In this final section we will forge the link to more conventional research on eye-movement control in reading. Fixation disparity has implications for conventional forms of data analysis. Typically, eye movement in reading data are analyzed in a word-based fashion, i.e., fixations are assigned to a given word in the reading material, or even to a letter within that word. We will focus on three examples illustrating the effects of horizontal fixation disparity. First, fixation disparity can lead to instances where the two eyes fixate on different words (with differing word characteristics like word length or frequency). The gaze trace in Figure 1b provides an example: During the 4th fixation, the right eye is located on the last letter of the word "Strom" while the left eye fixates at the beginning of the following word "mit". Consequently, fixation disparity can affect analyses of fixation probabilities, which require post-hoc assignment of an eye movement to a certain saccade type (one-word forward saccade, skipping, refixation, regression). For example, in Figure 1 the word "Strom" receives a single fixation from the right eye but is skipped by the left eye. Note that due to the overall disparity reduction during fixation, these fixation-location-related parameters potentially are subject to change from start to end of fixation. Second, fixation disparity can lead to differences in letter assignment for the two eyes, which has implications for landing-position-related phenomena like the Preferred Viewing Location (Rayner, 1979). Third, based on the observed patterns of eye disparities in reading, saccade amplitudes are expected to show an abduction–adduction asymmetry. We will now discuss these three points in more detail.

The two eyes do not always fixate on the same word

First, the horizontal disparity between eyes can lead to instances where the left eye and the right eye fixate on different words. When start-of-fixation disparities were considered, an impressive 15.2% (1.6 + 13.6) of fixations show such a different-word assignment (Table 3). When considering end-of-fixation disparities, this percentage somewhat dropped to 12.7% (1.5 + 11.2), as a result of vergence movements of the eyes. In most of these different-word cases, the left eye fixates on the word to the right of the word the right eye is on (Table 3), reflecting the predominantly crossed nature of nonaligned fixations in the present data set (Table 2).

	∑ Start (%)	End, same word	End, different word, uncrossed (L R)	End, different word, crossed (R L)
Normal				
∑ End (%)		87.3	1.5	11.2
Start, same word	84.8	82.4	0.5	1.8
Start, different word, uncrossed (L R)	1.6	0.7	0.9	0
Start, different word, crossed (R L)	13.6	4.2	0	9.4
Random				
∑ End (%)		84.8	1.7	13.4
Start, same word	81.9	79.1	0.6	2.2
Start, different word, uncrossed (L R)	1.9	0.8	1.0	0.04
Start, different word, crossed (R L)	16.2	4.9	0.1	11.2

Table 3. Effect of horizontal disparities on the assignment of eye fixations to words. The two eyes either fixate on the same word *n* or on different words; the latter configuration shows as either uncrossed (left eye fixates on previous word $n - 1$) or crossed (left eye fixates on next word $n + 1$). The table collects mean alignment proportions (%) at the start vs. end of fixations. In addition to the original data (normal), data for a random baseline are presented (random).

Notably, from start to end of fixation the word assignment for reading fixations can change. Some fixations actually change from same- to different-word assignment, but 4.9% of all fixations change from different- to same-word assignment. At first glance, this overall reduction of different-word assignments might suggest that vergence movements specifically aim at realigning the eyes at the target word (which would be one of the two fixated words). The hypothesis was tested against the null hypothesis of no such functionality by comparing the data to a random baseline (McDonald & Shillcock, 2005). For this purpose, the data were reprocessed in the following way: For each participant and sentence, the original word order and sequence of word lengths was destroyed by random permutation while the fixation order was preserved. This procedure altered the assignment of fixations to words in a sentence, providing a random baseline measure. The random data show the same qualitative pattern as the real data. From start to end of fixation, the percentage of different-word assignment dropped from 18.1% (1.9 + 16.2) to 15.2% (1.7 + 13.4), simply due to disparity-reducing vergence movements of the eyes.[6]

Note that the notion of target-directed vergence in reading cannot be tested directly. Due to noise in the

oculomotor system, the eyes frequently land on unintended words (Engbert & Nuthmann, 2008, based on right-eye data). In addition, the present binocular analyses suggest that the two eyes do not always fixate on the same word. For these instances (>10%), determining the target word poses an unresolved question even if we simplifying assume that the fixated word represents the intended target word. Yet, the following hypothesis can be derived: If vergence was target-directed, the net disparity reduction from start to end of fixation should be greater for fixations where both eyes initially fixated on different words as compared to the same word. To test this hypothesis, we sampled all binocular fixations with an absolute start-of-fixation disparity magnitude between 1.0 and 1.5 letters. The average net disparity reduction for different-word assignments was not larger than for same-word assignments [0.226 vs. 0.234 characters; $t(224) = 1.37$, $p = 0.17$]. (The sampling procedure was favored over a linear model because of the following interrelations: (1) different-word binocular fixations generally have a greater start-of-fixation disparity than same-word binocular fixations (means in characters: 1.77 vs. 1.11), and (2) net disparity reduction increases with increasing absolute start-of-fixation disparity ($r = 0.53$, $p < 0.001$).) We conclude that there is no statistical support for the assumption that vergence movements in reading specifically aim at realigning the eyes at the target word.

The preferred viewing location revisited

The following analyses investigate the effect of horizontal disparity between the eyes on within-word landing position distributions as a typical spatial measure of eye-movement control in reading. Previous investigations have shown that landing position distributions resemble truncated Gaussian distributions with a mean that is typically somewhat left of word center. The mean of the distribution was termed *Preferred Viewing Location* (PVL, Rayner, 1979). The phenomenon has been replicated many times, always based on data from one eye.

Here, we compare PVL curves obtained for right-eye data with data from the left eye. A number of data selection criteria were applied. To facilitate the comparison between eyes, only fixations that were assigned to the *same* word for right- and left-eye data were considered (see above). In addition, analyses were restricted to *single* fixations, i.e., the ideal instances where word identification required only one (single) fixation on a word. The word-length analysis was restricted to 3- to 8-letter words. All analyses were based on position values recorded at the end of fixation. For further comparison, data from the left and right eye were contrasted with data from a so-called average eye (see Appendix A). As an example, Figure 8a displays the observed PVL curves for 5-letter words. For statistical analyses, an empirical PVL curve was computed for each participant, eye, and words of a given length (3 to 8 letters). Following the procedure by Nuthmann, Engbert, and Kliegl (2007) normal curves were fitted to these data. Mean and standard deviation of the best-fitting normal curve determine the PVL curve. To obtain estimates for both parameters, a grid search method with a minimum-χ^2 criterion was used. Landing positions were standardized by dividing the letter position by word length, yielding values between 0 (i.e., for fixations on the space before the

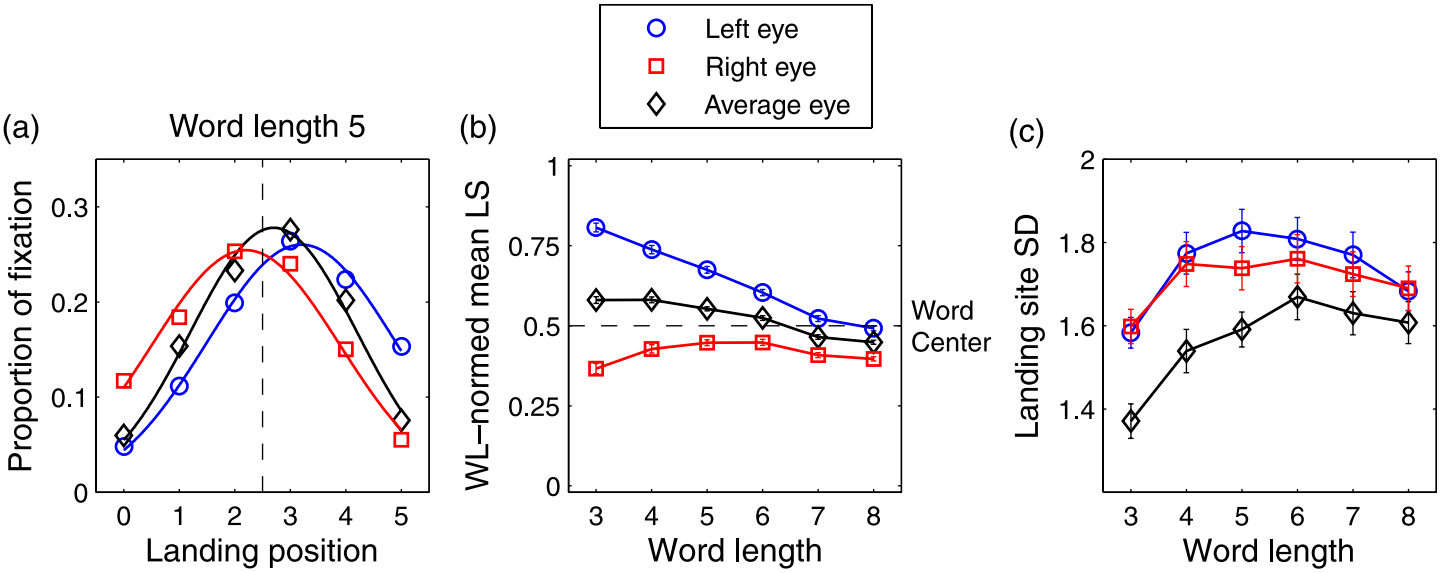

Figure 8. (a) Horizontal preferred viewing location as reflected by landing position distributions. Symbols represent empirical data, here from 5-letter words. Data from the right eye (red squares) were contrasted with data from the left eye (blue circles) and from an artificially created average eye (black diamonds). Normal curves were fit to empirical landing position distributions: Panels (b) and (c) display *M′* and *SD* of the fitted normal curve as a function of word length (see text for details). Broken vertical line (a) and broken horizontal line (b) represent the center of the word.

word) and 1. Participant-based means M' and standard deviations SD of the Gaussian landing position distributions were subjected to two 3 × 6 repeated measures ANOVAs with eye (left, right, average) and word length as within-participant factors.

Note that landing positions for the left and right eye were analyzed separately, i.e., as independent events. Nonetheless, distributions of within-word landing positions are a further illustration of the direction of the observed average horizontal fixational disparity. For a given word length, the landing position distribution for the left eye is clearly shifted to the right of that for the right eye (Figures 8a and 8b). Consistent with the aligned, crossed, and uncrossed data described above, on average, participants fixated less far into the word with the right eye than they did with the left eye.[7] For the average eye, the landing position distribution peaks at a value between the right-eye and left-eye PVLs. Statistical analyses showed a significant main effect of eye on the mean landing site [M': $F(2,223) = 368.3$, $MSe = 0.98$, $p < 0.001$] (Figure 8b). There is also a main effect of word length [M': $F(5,220) = 345.2$, $MSe = 0.87$, $p < 0.001$], which interacts with the effect of eye [M': $F(10,215) = 32.9$, $MSe = 0.10$, $p < 0.001$] indicating that eye-related differences in PVL are stronger for shorter words. Control analyses indicated that this interaction was due to a selection effect since short words were less likely to meet the same-word criterion. The same-word selection criterion also slightly altered the effect of word length typically observed: When considering single fixations from the right eye only, the PVL tends to shift a bit to the left as word length increases (Nuthmann & Kliegl, in press). As for the landing site standard deviation, both main effects and their interaction were significant (all Fs > 3.6). The most relevant finding here is probably that the standard deviation (of word-length dependent landing position distributions) is reduced for the average eye (Figure 8c). Analyses based on the average eye would thus yield more conservative estimates for the probability of so-called mislocated fixations, that is, fixations that miss their intended target word (Engbert & Nuthmann, 2008). In sum, the data suggest that the widely accepted notion of a preferred viewing location "slightly left of word center" (e.g., Nuthmann, Engbert, & Kliegl, 2005; Nuthmann & Kliegl, in press; Rayner, 1979) is only true for data recorded from the right eye. For left-eye data, we find a PVL that is located right of word center.

Abduction–adduction asymmetry for saccade lengths

Previous research based on a simple scanning paradigm reported systematic differences in horizontal saccades made by the abducting (i.e., temporally moving) vs. adducting (i.e., nasally moving) eye (Collewijn et al., 1988a). The saccades of the abducting eye had larger amplitudes, higher peak velocities, and shorter durations. There is a rather anecdotal report that this asymmetry was also found for the amplitudes of reading saccades (Heller & Radach, 1999). An implication of this asymmetry pattern is that post-saccadic eye disparities were predominantly uncrossed in these data. In the present data, however, negative (crossed) fixation disparities are most prevalent (Figure 3). In addition, the magnitude of disparity tends to increase as the eyes move through the sentence (Figure 6). The data should therefore show a reversed abduction–adduction asymmetry for saccade lengths. When reading Western languages, the majority of saccades are from left to right across the line of text. In this case, the right eye is the abducting eye while the left eye is the adducting eye. Consequently, a reversed abduction–adduction asymmetry predicts larger amplitudes for the left (adducting) eye. Indeed, when collapsing the data across alignment conditions, the mean forward saccade length for the left eye was longer (7.8 character spaces, $SE = 0.10$) than for the right eye (7.5 character spaces, $SE = 0.10$). A paired 2-sample t-test indicated that this difference is significant [$t(224) = 13.7$, $p < 0.001$]. To clarify the causal relationship: The asymmetry between saccades made by the two eyes leads to post-saccadic eye disparities. The observed asymmetry in saccade lengths is reminiscent of the long-standing theoretical question whether the saccades of each eye are programmed independently or driven by a single neural signal (see Liversedge, Rayner, White, Findlay, & McSorley, 2006, for discussion).

Discussion

There is a wealth of empirical and computational research on various oculomotor and linguistic aspects of eye-movement control in reading (see Rayner, 1998, for a review). In comparison, literature on binocular coordination in normal continuous reading is rather sparse. The contribution of the present work can be summarized in two general points. First, we extended the existing literature on binocular coordination in reading. Second, based on a few selected examples we showed that key findings on binocular coordination obtained with simple scanning paradigms generalize to reading, i.e., an ecologically valid task involving sequences of saccades. We will discuss both points in turn.

In reading, the eyes make horizontal saccades, mostly from left to right. During fixations, the text material is visually processed. Contrary to a long-standing implicit assumption, the two eyes do not always fixate at the same location (Heller & Radach, 1999; Liversedge, White et al., 2006). In the present paper, the disparity of binocular reading fixations was investigated on both the horizontal and vertical dimensions. The observed data follow a 2-dimensional Gaussian distribution indicating that the

following pattern was most prevalent: The left eye is located further to the right than the right eye and fixates somewhat above the right eye (Figure 3). Importantly, the fact that disparities do not spread around a mean of nil disparity indicates that the disparity effects reported here are unlikely to be due to noise in the eye tracking system (see Liversedge, White et al., 2006, for a similar argument). Horizontal and vertical fixation disparities turned out to be largely uncorrelated. The mean magnitude of vertical disparity was somewhat smaller than the magnitude of horizontal disparities. In the following, we will compare the results for horizontal disparities with results obtained in other studies. The mean absolute magnitude of disparities as well as the proportion of aligned fixations was similar to what has been reported elsewhere (Blythe et al., 2006; Juhasz et al., 2006; Liversedge, White et al., 2006). From start to end of fixation, an overall reduction of fixation disparity was observed (Liversedge, White et al., 2006; but see Blythe et al., 2006). Interestingly, most disparate fixations showed crossed disparity, which differs from recent data showing the exact opposite pattern (Blythe et al., 2006; Juhasz et al., 2006; Liversedge, Rayner et al., 2006; Liversedge, White et al., 2006). Magnitude of fixation disparity and type of alignment change as the eyes move across the sentence (cf., Figure 6). Specifically, as the eyes moved from left to right through a sentence the magnitude of fixation disparity systematically increased (supporting Heller & Radach, 1999, but in disagreement with Liversedge, White et al., 2006). In addition, it was shown that net disparity reduction from start to end of fixation increased during the course of successive fixations while this was further modulated by incoming saccade length and fixation duration. In a first attempt to understand the differences between the present data and other data (most of all results reported by Liversedge and colleagues), we will pinpoint differences between the studies and discuss them in the light of their importance. We will then summarize conclusions that can be drawn from the analyses reported here.

The differences between the present study and the experimental setup used by Liversedge and colleagues are related to:

1. the eye trackers used,
2. the calibration procedure employed,
3. saccade detection (algorithm based vs. by hand),
4. viewing distance (50/60 cm vs. 100 cm),
5. the size of a letter in visual angle (0.45/0.38° vs. 0.19–0.29°),
6. constraints to reduce and/or eliminate head movements (chin rest vs. bite bar),
7. color combination of text presentation (black on a white background vs. white on a black background),
8. the illumination of the testing room (dimly lit vs. dark), and finally
9. the language (German vs. English).

First of all, the present data were collected using video-based SR Research EyeLink systems, which allow binocular recordings (see Methods section). In the other studies, binocular eye movements were recorded using left and right DPI eye trackers (i.e., a separate eye tracker for each eye). Besides, readers' eye fixations were calibrated binocularly while monocular calibrations on separate eye trackers were performed in the other studies. We argue that our results do not stem from the eye trackers used and the applied binocular calibration procedure for several reasons. First, in a recent reading study using an Eyelink II system, each eye was calibrated independently under monocular viewing conditions. As in the present study, a prevalence of crossed fixation disparities was observed (Shillcock, Roberts, Kreiner, & Obregon, 2009). Second, in the present study 13 readers (6%) showed more uncrossed than crossed fixations, showing that the experimental setup generates both overall patterns (for a discussion of individual differences, see below). Third, an analysis of monocular contributions to intra-fixational vergence showed different directional patterns for crossed vs. uncrossed fixation disparities (Figure 4). Observing such a dissociation strongly supports the validity of the applied measurement procedure: If the observed pattern of crossed and uncrossed disparities was distorted by the measurement procedure, the data should not show this dissociation. Fourth, we investigated the spatial distance between the binocular fixation point and the plane of text presentation. The corresponding distribution peaked about 2.6 cm in front of the text (i.e., the surface of the monitor) reflecting that negative disparities were most prevalent (Figure 7d). Notably, the positive disparities formed the right tail of the observed Gaussian distribution. Likewise, positive and negative horizontal fixation disparities are simply part of a Gaussian distribution of disparity magnitudes (Figure 3). From this perspective, the differences between the present data and other data boil down to the following question: What factors make the peak of the magnitude-of-disparity distribution shift from *negative* (here) to *positive* (prediction for data by Liversedge et al.), and why does the distribution not peak at zero disparity? Likewise, what makes the distribution describing the binocular fixation point peak at a position slightly *in front* of the monitor of text (here) vs. *behind* it (prediction for data by Liversedge et al.), and why does it not peak directly at the plane of text?

Jaschinski, Svede, and Jainta (2008) recently proposed a relationship between fixation disparity in reading and individual differences in vergence response. In their study, a subjective nonius procedure was used to examine individual differences in vergence performance. The data support a model that relates fixation disparity to vergence dynamics (Patel, Jiang, & Ogmen, 2001). The model predicts that the static vergence error (i.e., fixation disparity) is a result of asymmetric dynamic responsiveness of the disparity vergence mechanism in the convergent and divergent directions. Specifically, if divergent

velocity is larger (smaller) than convergent velocity, an uncrossed (crossed) fixation disparity will result. Accordingly, Jaschinski et al. (2008) relate the prevalence of uncrossed fixation disparities observed by Liversedge and colleagues to individual differences. It is suggested that uncrossed fixation disparities predominantly occur in subjects with a weak disparity convergence response. The subjects thus tend to under-converge; as a consequence, the lines of sight intersect behind the plane of text, yielding uncrossed fixation disparities. According to this hypothesis, most subjects in the present sample should show a weak divergence response, leading to over-convergence and crossed fixation disparities.

While Jaschinski et al. (2008) relate the direction of fixation disparity to individual differences, Kirkby et al. (2008) make the case for developmental differences in the alignment of fixation disparity. Younger children's eyes tend to become transiently converged during saccades (Fioravanti, Inchingolo, Pensiero, & Spanio, 1995), which should be accompanied by an increased proportion of crossed disparity during fixations (Blythe et al., 2006). In contrast, the eyes of older children and adults show a transient divergence during saccades (Fioravanti et al., 1995; for adults see also Collewijn et al., 1988a), which should be accompanied by a majority of uncrossed fixations (Liversedge, White et al., 2006). Individual differences and developmental aspects were clearly not the focus of the present paper, but the following formal argument can be derived: As for individual differences, in the present study only 13 out of 225 readers (6%) showed more uncrossed than crossed fixations. In contrast, in a study by Juhasz et al. (2006) this was the case for 9 out of 12 readers (75%). There is no indication that different laboratories selectively sampled readers with under-convergence (Liversedge and colleagues) or over-convergence (present study, see also Shillcock et al., 2009). In addition, the fact that 212 out of 225 adult readers in our database show more crossed than uncrossed disparities casts some doubt on the hypothesis of developmental differences, at least as far as the direction of fixation disparity is concerned. Kirkby et al. (2008) implicitly ascribe a specific advantage to uncrossed fixation disparities (see also Kloke & Jaschinski, 2006). Owing to differences in the data currently available, drawing this conclusion seems premature. At this point, we suggest the following: Differences in the direction of fixation disparities across different studies simply reflect that the visual system is able to flexibly adjust to different stimulus configurations. We conclude that the marked differences across studies suggest that not only individual differences and developmental aspects but also factors related to the experimental setting determine whether the adopted fixation disparity is predominantly crossed or uncrossed. Put differently, differences in the experimental setting might induce differences in vergence response. The above listing points to possible candidates. For example, in the present study sentences were presented in black on a white background. This high contrast could have led to a systematic misperception of depth. The impact of viewing distance is another factor calling for systematic investigation. Viewing distance and font size jointly determine the visual angle a character subtends. Careful systematic experimental manipulation of these factors is an inevitable avenue for future research. Potentially, the outcome of this research is relevant for the ergonomic design of computer workstations (see Jaschinski, 2002, for utilizing fixation disparity as an indicator of near vision fatigue). In sum, future research will have to map out more precisely what factors shift the distribution of the binocular fixation point (Figure 7d), both at the sample level but also at the level of the individual. Finally, this is the first study to provide exploratory analyses of vertical disparities. As an observation we report that, on average, the left eye tends to fixate slightly above the right eye. Future research needs to determine the underlying mechanisms.

A great deal has been learned about the nature of binocular eye movements from studies using simple stimuli (LEDs) with highly constrained task demands (e.g., asking observers to look back and forth between visual stimuli). Many such studies use only a small number of subjects who are often experienced in eye-movement research. Here, eye-movement data during reading were collected from a large number of naive subjects. Results showed that key findings from basic research on binocular coordination generalize to reading. Most notably, we investigated how eye disparity changes during the time course of successive saccades and fixations. The data showed a transient pattern of disparity increase–reduction (Figure 5). During a saccade, mean unsigned eye disparity initially strongly increases but decreases later on. During the subsequent fixation, disparity is further reduced (e.g., Collewijn et al., 1988a, 1997). The vergence pattern during saccades originates from an asymmetry between saccades made by the abducting and adducting eye (Collewijn et al., 1988a). However, given the observed prevalence of negative disparities, the asymmetry showed a direction opposite to what has been observed elsewhere (e.g., Collewijn et al., 1988a). That means, in the present reading data, the left (adducting) eye had a larger amplitude than the right (abducting) eye.

Furthermore, an analysis of monocular contributions to intra-fixational (or post-saccadic) vergence indicated a left–right eye asymmetry (cf. Enright, 1998)[8]: Changes in monocular fixation positions from start to end of fixation indicated a higher monocular activity of the right eye as compared to the left eye (Figure 4). Different to the analyses employed here, Enright (1998) established the asymmetry of post-saccadic vergence based on deviations between eye positions and target positions. To reiterate, the underlying assumption is that vergence aims at obtaining alignment of both eyes on the target position and/or correcting for changes in depth. Indeed, it has been proposed that post-saccadic drift is target-directed and

thus functional (Collewijn et al., 1988a). In basic studies on binocular coordination, subjects are asked to make gaze shifts to a well-defined target in space. Targets for reading saccades are not as well defined. Reading is inherently dynamic and requires to program sequences of saccades with variable amplitudes. There is the widely held assumption that reading saccades have a functional target (cf., Radach & Kennedy, 2004), which would be a word and, at least for inter-word saccades, the center of that word (McConkie, Kerr, Reddix, & Zola, 1988). Due to oculomotor error, the eyes quite frequently undershoot or overshoot the center of the word, or miss the intended target word altogether (Engbert & Nuthmann, 2008). From this perspective, it appears unlikely that vergence movements in reading specifically aim at aligning the eyes on the presumed target position, i.e., the center of the word as the optimal viewing position. As a matter of fact, in more than 10% of all considered fixations the left and right eyes did not even fixate on the same word. Compared to the start of fixation, at the end of fixation the percentage of different-word assignments was reduced (Table 3), due to disparity-reducing vergence. However, our analyses did not support the hypothesis that intra-fixational vergence movements specifically aim at realigning the eyes at the target word. This brings us to a more general question: What is the purpose of vergence in reading? In the present experiment, participants read sentences on an approximately flat screen with straight-ahead view at the center of the monitor. The geometry of such a setting indicates only slight changes in depth when moving the eyes across the sentences (cf., Figure 7a). In comparison to other tasks, vergence changes observed in reading are indeed small, but they occur systematically. In principle, the vergence state of the eyes is useful to obtain an estimate of object distance as there is a direct relationship between vergence angle and viewing distance (see Welchman & Harris, 2003, for discussion). As outlined above, the oculomotor system is not very accurate as far as spatial aspects of saccade programming are concerned. Apparently, this also holds for positioning the eyes relative to each other. However, the data reported here indicate that the vergence-related net disparity reduction from start to end of fixation systematically increased as the eyes moved from left to right through the sentence (Figures 6a and 7c). This suggests that the visuo-oculomotor system tolerates the accumulation of fixation disparity only to a certain degree. In sum, it is concluded that adjustments in vergence reduce fixational and retinal disparities to maintain single binocular vision. Based on this conclusion, the following prediction can be derived: The magnitude of accumulated fixation disparity, which elicits a stronger vergence response, should be close to the upper disparity tolerance for fusion. The mean magnitude of the accumulated start-of-fixation disparity depicted in Figure 6 translates into about 35 arc min. This is in line with the upper disparity limit of about 32–40 min of arc reported by Qin et al. (2006). However, such comparison should be treated cautiously, for several reasons. First, studies on Panum's fusional area exclusively use non-linguistic sparse stimuli. Second, the size of Panum's fusional area is not hard-wired and varies with several stimulus parameters (see Schor, Heckmann, & Tyler, 1989, for discussion). Third, conventional methods of estimating fusion limits might be inappropriate to reflect the dynamics of visual processing in reading. Finally, such comparison is based on the assumption that the magnitude of fixation disparity is a good enough approximation of some corresponding retinal disparity.

Bridging the gap to more conventional research on eye-movement control in reading, the present paper also investigated the effect of horizontal eye disparity on spatial measures of eye-movement control in reading, notably on the well-established horizontal preferred viewing location. Readers fixated further into the word with the left eye than with the right eye (Figure 8). The direction of the observed shift in landing position distribution is consistent with the fact that the most prevalent type of disparate fixation is crossed. Thus, aspects of the Preferred Viewing Location (Rayner, 1979) are modulated by which eye is considered. The effect of eye depends on the overall direction of the observed fixation disparity (see Liversedge, White et al., 2006, for a left-eye shift of the PVL in the opposite direction). Finally, observing a majority of crossed disparities has consequences for experiments utilizing the so-called boundary technique (Rayner, 1975). In a typical boundary experiment, a single critical target word is initially replaced by another word or by a nonword. When the reader's saccade crosses over an invisible pre-specified boundary location in the text, the initially displayed stimulus is replaced by the target word. Typically, the implementation of the boundary is based on real-time position information from the *right* eye. However, in case of crossed fixation disparity, the left eye is already past the boundary and might already fixate on the mask. Therefore, the present data suggest that the implementation of the invisible boundary should rely on information from the currently rightmost eye; this would of course require binocular recordings.

Conclusions

Based on a large data set of 225 readers, the present data complement what we currently know about binocular eye movements in reading while the approach taken here draws inspiration from basic research using standard oculomotor aiming tasks. The present analyses showed that in reading, the version and vergence system interact in a way that is qualitatively similar to what has been observed in simple nonreading tasks. The traditional description of the human binocular system suggests that the two lines of sight always intersect at the fixated

object, resulting into a simple trigonometric arrangement between the centers of the two eyes and the object. Such a trigonometry is found in textbooks (e.g., Figure 2.6 in Hershenson, 1999) and also forms the basis for conventional analyses of retinal disparity processing and stereopsis (see Read, 2005, for a review of current neural models of stereopsis). Analyses of the binocular fixation point presented here strongly challenge this traditional thinking (see Hillis & Banks, 2001, for a discussion of errors in retinal disparity estimates caused by fixation disparity). Different than in other reading and nonreading studies, fixation disparity in our reading corpus data is predominantly crossed (i.e., the left eye being to the right of the right eye). Differences in the direction of fixation disparities across studies indicate that the visual system is able to flexibly respond to different stimulus configurations. Given that horizontal fixation disparity affects standard measures of eye-movement control in reading, it seems desirable that computational models of eye-movement control in reading (see Reichle, Rayner, & Pollatsek, 2003, for a review) start to take key findings from binocular studies into account.

Appendix A

Saccade detection and raw data processing

For saccade detection a velocity-based detection algorithm originally developed for the analyses of microsaccades (Engbert & Kliegl, 2003b) was used (updated by Engbert & Mergenthaler, 2006). Saccades are distinguished from fixations by changes of velocity values (Engbert & Kliegl, 2003a). First, the time series of eye positions is transformed to velocities with a weighted moving average of velocities over five data samples to suppress noise. As a consequence of the random orientations of the velocity vectors during fixations, the resulting mean value is effectively zero (Figure A1). In this representation, saccades can be identified by their velocities, which are clearly separated from the kernel of the distribution, that is, saccades are "outliers" in velocity space.

Second, for a given eye and trial (i.e., sentence) median-based velocity thresholds were computed. Because these computations are performed separately for horizontal and vertical velocity components, the corresponding thresholds define an ellipse in the velocity space (Figure A1). However, when reading a one-line sentence the eyes predominantly move horizontally so that the horizontal component is most important. If there are more than three (for data from SR EyeLink I system) and/or 4 (for data from SR EyeLink II system) velocity samples falling outside this ellipse, these sequences are defined as saccades. Third, binocular reading saccades are defined as saccades occurring in the left and right eyes with a temporal overlap (see Engbert & Kliegl, 2003a, for details on the implementation). Finally, to qualify as a reading saccade, the amplitudes of saccades in both eyes had to exceed one letter. Consequently, saccades with smaller amplitudes were qualified as intra-fixational movements, i.e., microsaccades.

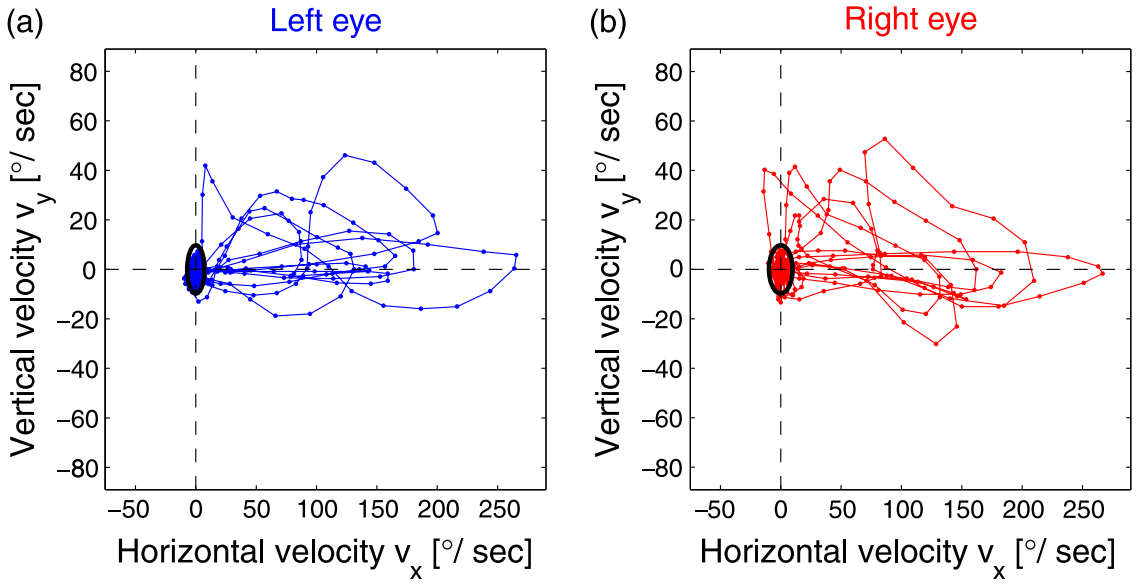

Figure A1. Example of binocular saccades. (a) Data recorded from the left eye. (b) Data recorded from the right eye. The trajectory from Figure 1, recorded with an SR EyeLink II system, is now plotted in 2-D velocity space. The ellipse in each panel is defined by the velocity thresholds of the saccade detection algorithm. If there are more than three (for data from SR EyeLink I system) and/or four (for data from SR EyeLink II system) velocity samples falling outside this ellipse, these sequences are defined as saccades.

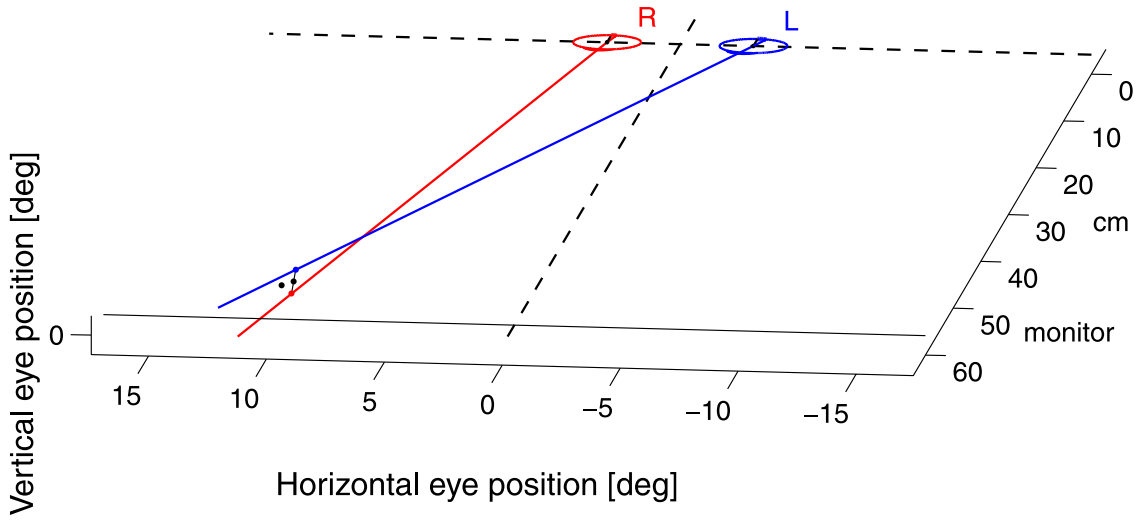

Figure A2. Schematic visualization of a crossed fixation with exaggerated horizontal and vertical disparities. Three-dimensional view from behind the monitor. The blue line represents the principal line of sight for the left eye, the red line for the right eye. The shortest distance between these two lines is marked in black. The middle point on this line defines the binocular fixation point in 3-D space. For comparison, the single black dot marks the binocular fixation point determined in 2-D space, see Footnote 5.

Following saccade detection, data were further processed to create a matrix format where each row represents one fixation, and numerous columns carry relevant information about this fixation as well as the preceding and outgoing saccade. Four of these matrices were created: matrix *LS* and *RS* coded left-eye (*L*) and right-eye (*R*) data as recorded at the start of fixation (*S*) while matrix *LE* and *RE* coded spatial and temporal eye-movement measures with regard to the end of fixation (*E*). For some analyses, two further matrices *LM* and *RM* were created where information was coded with regard to fixation position values that were averaged across the whole fixation. Finally, analyses on the preferred viewing location included data from an "average eye." For this purpose, an average gaze trace was created by averaging raw gaze position values across both eyes; this was done for data from each trial, separately for horizontal and vertical eye positions. Sequences of saccades and fixations were determined based on these average gaze traces.

Binocular fixation point

A unique binocular fixation point only exists if both lines of sight are in a single plane of regard. In such a case, the binocular fixation within this plane is defined by the azimuth (i.e., horizontal rotation) angles of the two eyes (cf., Collewijn et al., 1997, for an analysis of the spatial trajectories of the binocular fixation point during saccades in a simple scanning task). In cases where the eyes show vertical disparity and the lines of sight thus do not intersect, the binocular fixation point can be operationally defined as the site of shortest distance between the two lines of sight. In 3-D space, two lines, *AB* and *CD*, are defined by four specified points, $A(x, y, z)$, $B(x, y, z)$, $C(x, y, z)$, and $D(x, y, z)$. Here, *AB* denotes the line of sight for the left eye while *CD* denotes the visual line for the right eye. *A* and *C* are determined by the center of rotation of the left and right eyes, respectively. *B* and *D* represent the respective fixation positions, as measured with the eye tracker. The shortest distance between any pair of lines is the length of the line that is perpendicular to both lines (Bowyer & Woodwark, 1983). The middle point on this line defines the site of shortest distance between two lines *AB* and *CD* in 3-D space. (All geometrical calculations were done using the Geometry Library for Matlab provided by John Burkardt.) For clarification, Figure A2 visualizes a simulated crossed fixation with exaggerated horizontal and vertical disparities (see also Movies 1 and 2).

Acknowledgments

Data collection was funded by DFG Grant KL 955/6. A.N. was funded by the same grant when she held a position at the University of Potsdam. We are grateful to Ralph Radach, Gordon Legge, and an anonymous reviewer for their thoughtful comments on the manuscript. A.N. would further like to thank Richard Shillcock, Matthew Roberts, and Hamutal Kreiner for their feedback on this research.

Commercial relationships: none.
Corresponding author: Antje Nuthmann.

Email: Antje.Nuthmann@ed.ac.uk.
Address: Department of Psychology, University of Edinburgh, 7 George Square, Edinburgh EH8 9JZ, UK.

Footnotes

[1]Note that a few selected binocular aspects were briefly described elsewhere (Kliegl et al., 2006).

[2]Note that 11 readers did not produce uncrossed fixation disparities at all; the data points were treated as missing values.

[3]Interestingly, Collewijn et al. (1995) report to have encountered "a few rare individuals" who also showed such an "opposite pattern of transient vergence" (p. 3339).

[4]In part, this relationship was due to the selection criterion of forward saccade sequences.

[5]For the sake of completeness it should be mentioned that this clear-cut dissociation is only true if the eyes are iso-elevated (i.e., $D_y = 0$). There are exceptions to this rule if I_y (i.e., the vertical component of the binocular fixation point) is determined by taking vertical disparity ($D_y \neq 0$) into account. In the latter case, I_y is somewhat smaller than the I_y that we would obtain based on the simplifying assumption of $D_y = 0$. As a consequence, for some positive (uncrossed) fixations, I_y actually shows slightly in front of the monitor rather than beyond it, as can be seen in Figure 7e.

[6]Note that the randomization procedure leads to broader landing position distributions with more fixations falling on word beginnings and word ends (cf. Figure 1 in McDonald & Shillcock, 2005). This leads to a somewhat higher baseline probability of different-word assignment.

[7]Consequently, when observing a prevalence of uncrossed fixation disparities, the PVL is shifted in the opposite direction (Liversedge, White et al., 2006).

[8]Note that both the present approach and Enright's approach are indirect tests.

References

Baayen, R. H. (2008). *Analyzing linguistic data: A practical introduction to statistics using R*. Cambridge, UK: University Press.

Bates, D. (2007). lme4: Linear mixed-effects models using S4 classes (R package version 0.99875-9).

Blythe, H. I., Liversedge, S. P., Joseph, H. S., White, S. J., Findlay, J. M., & Rayner, K. (2006). The binocular coordination of eye movements during reading in children and adults. *Vision Research, 46,* 3898–3908. [PubMed]

Bowyer, A., & Woodwark, J. (1983). *A programmer's geometry*. Butterworths.

Cassin, B., & Rubin, M. L. (2006). *Dictionary of eye terminology* (5th ed.). Gainesville, FL: Triad Publishing Company.

Collewijn, H., Erkelens, C. J., & Steinman, R. M. (1988a). Binocular co-ordination of human horizontal saccadic eye movements. *The Journal of Physiology, 404,* 157–182. [PubMed] [Article]

Collewijn, H., Erkelens, C. J., & Steinman, R. M. (1988b). Binocular co-ordination of human vertical saccadic eye movements. *The Journal of Physiology, 404,* 183–197. [PubMed] [Article]

Collewijn, H., Erkelens, C. J., & Steinman, R. M. (1995). Voluntary binocular gaze-shifts in the plane of regard: Dynamics of version and vergence. *Vision Research, 35,* 3335–3358. [PubMed]

Collewijn, H., Erkelens, C. J., & Steinman, R. M. (1997). Trajectories of the human binocular fixation point during conjugate and non-conjugate gaze-shifts. *Vision Research, 37,* 1049–1069. [PubMed]

Cornell, E. D., MacDougall, H. G., Predebon, J., & Curthoys, I. S. (2003). Errors of binocular fixation are common in normal subjects during natural conditions. *Optometry and Vision Science, 80,* 764–771. [PubMed]

Engbert, R., & Kliegl, R. (2003a). Binocular coordination in microsaccades. In J. Hyönä, R. Radach, & H. Deubel (Eds.), *The mind's eyes: Cognitive and applied aspects of oculomotor research* (pp. 103–117). Oxford, UK: Elsevier.

Engbert, R., & Kliegl, R. (2003b). Microsaccades uncover the orientation of covert attention. *Vision Research, 43,* 1035–1045. [PubMed]

Engbert, R., & Mergenthaler, K. (2006). Microsaccades are triggered by low retinal image slip. *Proceedings of the National Academy of Sciences of the United States of America, 103,* 7192–7197. [PubMed] [Article]

Engbert, R., & Nuthmann, A. (2008). Self-consistent estimation of mislocated fixations during reading. *PLoS ONE, 3,* e1534. [PubMed] [Article]

Engbert, R., Nuthmann, A., Richter, E. M., & Kliegl, R. (2005). SWIFT: A dynamical model of saccade generation during reading. *Psychological Review, 112,* 777–813. [PubMed]

Enright, J. T. (1998). Monocularly programmed human saccades during vergence changes? *The Journal of Physiology, 512,* 235–250. [PubMed] [Article]

Fioravanti, F., Inchingolo, P., Pensiero, S., & Spanio, M. (1995). Saccadic eye movement conjugation in children. *Vision Research, 35,* 3217–3228. [PubMed]

Heckmann, T., & Schor, C. M. (1989). Panum's fusional area estimated with a criterion-free technique. *Perception & Psychophysics, 45,* 297–306. [PubMed]

Heller, D., & Radach, R. (1999). Eye movements in reading: Are two eyes better than one? In W. Becker, H. Deubel, & T. Mergner (Eds.), *Current oculomotor research. Physiological and psychological aspects* (pp. 341–348). New York: Kluwer Academic, Plenum.

Hendriks, A. W. (1996). Vergence eye movements during fixations in reading. *Acta Psychologica, 92,* 131–151. [PubMed]

Hering, E. (1868). *Die Lehre vom binokularen Sehen [The theory of binocular vision]*. Leipzig, Germany: Engelman.

Hershenson, M. (1999). *Visual space perception*. London: The MIT Press.

Hillis, J. M., & Banks, M. S. (2001). Are corresponding points fixed? *Vision Research, 41,* 2457–2473. [PubMed]

Hung, G. K., Zhu, H., & Ciuffreda, K. J. (1997). Convergence and divergence exhibit different response characteristics to symmetric stimuli. *Vision Research, 37,* 1197–1205. [PubMed]

Jaschinski, W. (2002). The proximity-fixation-disparity curve and the preferred viewing distance at a visual display as an indicator of near vision fatigue. *Optometry and Vision Science, 79,* 158–169. [PubMed]

Jaschinski, W., Svede, A., & Jainta, S. (2008). Relation between fixation disparity and the asymmetry between convergent and divergent disparity step responses. *Vision Research, 48,* 253–263. [PubMed]

Juhasz, B. J., Liversedge, S. P., White, S. J., & Rayner, K. (2006). Binocular coordination of the eyes during reading: Word frequency and case alternation affect fixation duration but not fixation disparity. *Quarterly Journal of Experimental Psychology, 59,* 1614–1625. [PubMed]

Kirkby, J. A., Webster, L. A., Blythe, H. I., & Liversedge, S. P. (2008). Binocular coordination during reading and non-reading tasks. *Psychological Bulletin, 134,* 742–763. [PubMed]

Kliegl, R., Grabner, E., Rolfs, M., & Engbert, R. (2004). Length, frequency, and predictability effects of words on eye movements in reading. *European Journal of Cognitive Psychology, 16,* 262–284.

Kliegl, R., Nuthmann, A., & Engbert, R. (2006). Tracking the mind during reading: The influence of past, present, and future words on fixation durations. *Journal of Experimental Psychology: General, 135,* 12–35. [PubMed]

Kloke, W. B., & Jaschinski, W. (2006). Individual differences in the asymmetry of binocular saccades, analysed with mixed-effects models. *Biological Psychology, 73,* 220–226. [PubMed]

Lehrl, S. (1977). *Mehrfach-Wortschatz-Test Form B [Multiple-choice vocabulary test]*. Erlangen, Germany: Perimed.

Liversedge, S. P., Rayner, K., White, S. J., Findlay, J. M., & McSorley, E. (2006). Binocular coordination of the eyes during reading. *Current Biology, 16,* 1726–1729. [PubMed] [Article]

Liversedge, S. P., White, S. J., Findlay, J. M., & Rayner, K. (2006). Binocular coordination of eye movements during reading. *Vision Research, 46,* 2363–2374. [PubMed]

McConkie, G. W., Kerr, P. W., Reddix, M. D., & Zola, D. (1988). Eye movement control during reading: I. The location of initial eye fixations on words. *Vision Research, 28,* 1107–1118. [PubMed]

McDonald, S. A., & Shillcock, R. C. (2005). Toward an appropriate baseline for measures of eye movement behavior during reading. *Journal of Experimental Psychology: Human Perception and Performance, 31,* 584–591. [PubMed]

Morrison, R. E., & Rayner, K. (1981). Saccade size in reading depends upon character spaces and not visual angle. *Perception & Psychophysics, 30,* 395–396. [PubMed]

Nuthmann, A. (2006). The "where" and "when" of eye fixations in reading (Doctoral dissertation, University of Potsdam, http://nbn-resolving.de/urn:nbn:de:kobv:517-opus-7931).

Nuthmann, A., Engbert, R., & Kliegl, R. (2005). Mislocated fixations during reading and the inverted optimal viewing position effect. *Vision Research, 45,* 2201–2217. [PubMed]

Nuthmann, A., Engbert, R., & Kliegl, R. (2007). The IOVP effect in mindless reading: Experiment and modeling. *Vision Research, 47,* 990–1002. [PubMed]

Nuthmann, A., & Kliegl, R. (in press). Preferred viewing locations: A validation and an extension. *Perception*.

Patel, S. S., Jiang, B. C., & Ogmen, H. (2001). Vergence dynamics predict fixation disparity. *Neural Computation, 13,* 1495–1525. [PubMed]

Qin, D., Takamatsu, M., & Nakashima, Y. (2006). Disparity limit for binocular fusion in fovea. *Optical Review, 13,* 34–38.

Radach, R., & Kennedy, A. (2004). Theoretical perspectives on eye movements in reading: Past controversies, current issues and an agenda for future research. *European Journal of Cognitive Psychology, 16,* 3–26.

Rashbass, C., & Westheimer, G. (1961). Disjunctive eye movements. *The Journal of Physiology, 159,* 339–360. [PubMed] [Article]

Rayner, K. (1975). The perceptual span and peripheral cues in reading. *Cognitive Psychology, 7,* 65–81.

Rayner, K. (1979). Eye guidance in reading: Fixation locations within words. *Perception, 8,* 21–30. [PubMed]

Rayner, K. (1998). Eye movements in reading and information processing: 20 years of research. *Psychological Bulletin, 124,* 372–422. [PubMed]

R Development Core Team (2008). *R: A language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing. ISBN 3-900051-07-0.

Read, J. (2005). Early computational processing in binocular vision and depth perception. *Progress in Biophysics and Molecular Biology, 87,* 77–108. [PubMed] [Article]

Reichle, E. D., Rayner, K., & Pollatsek, A. (2003). The E-Z Reader model of eye-movement control in reading: Comparisons to other models. *Behavioral and Brain Sciences, 26,* 445–476. [PubMed]

Schor, C., Heckmann, T., & Tyler, C. W. (1989). Binocular fusion limits are independent of contrast, luminance gradient and component phases. *Vision Research, 29,* 821–835. [PubMed]

Schor, C., Wood, I., & Ogawa, J. (1984). Binocular sensory fusion is limited by spatial resolution. *Vision Research, 24,* 661–665. [PubMed]

Shillcock, R. C., Roberts, M. A. J., Kreiner, H., & Obregon, M. (2009). Binocular Foveation in reading. Manuscript submitted for publication.

Straumann, D. (2007). Disconjugate eye movements. In W. Behrens-Baumann (Ed.), *Neuro-Opthalmology* (vol. 40, pp. 90–109). Basel, Switzerland: Karger.

Wechsler, D. (1964). *Der Hamburg Wechsler Intelligenztest für Erwachsene (HAWIE) [The Hamburg Wechsler Intelligence Test for Adults]*. Bern, Switzerland: Huber.

Welchman, A. E., & Harris, J. M. (2003). Task demands and binocular eye movements. *Journal of Vision, 3*(11):15, 817–830, http://journalofvision.org/3/11/15/, doi:10.1167/3.11.15. [PubMed] [Article]

Yang, Q., & Kapoula, Z. (2003). Binocular coordination of saccades at far and at near in children and in adults. *Journal of Vision, 3*(8):3, 554–561, http://journalofvision.org/3/8/3/, doi:10.1167/3.8.3. [PubMed] [Article]

Yarbus, A. L. (1957). Motion of the eye on interchanging fixation points at rest in space. *Biophysics, 2,* 679–683.

Zee, D. S., Fitzgibbon, E. J., & Optican, L. M. (1992). Saccade–vergence interactions in humans. *Journal of Neurophysiology, 68,* 1624–1641. [PubMed]